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Towards direct detection of Exo-planets

using the Electric Field Conjugation Algorithm

Amir Give'on
Jet Propulsion Laboratory

Collaborators:

JPL: Brian Kern, Stuart Shaklan, Dwight Moody.

Game plan

- I am going to show that all correction algorithms can be written as a solution to the same equation (the devil is in the details).
- I will explain what EFC is.
- I will show the best DM diversity-based reconstruction algorithm we have so far.
- I will show experimental results for two types of coronagraphs to show the flexibility of the algorithm.

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All correction algorithms do the same thing...

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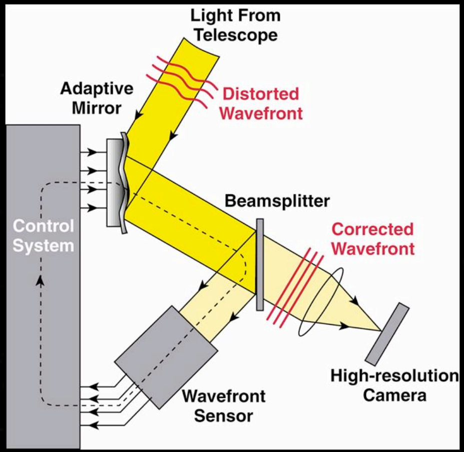

Figure by Claire Max

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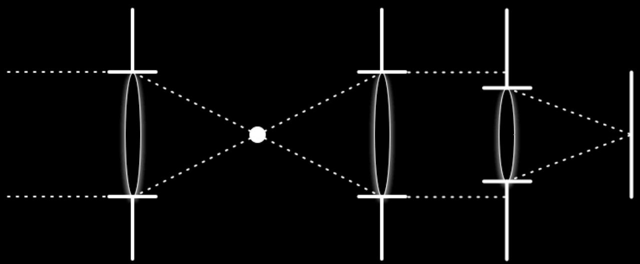

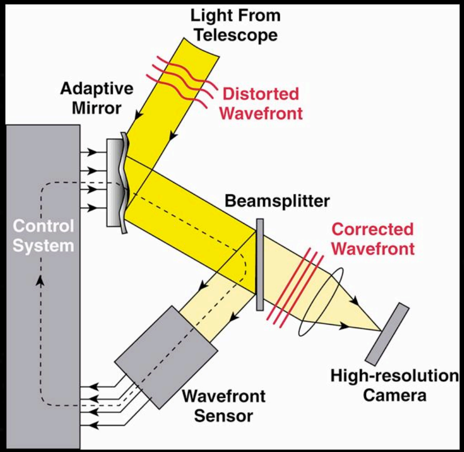

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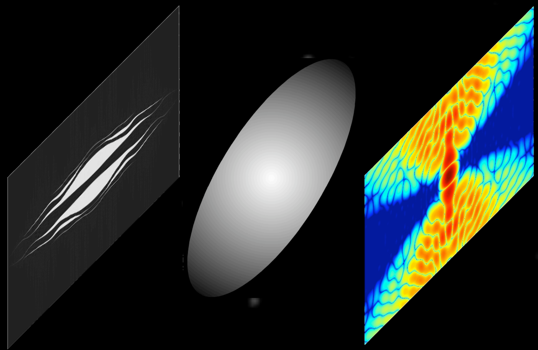

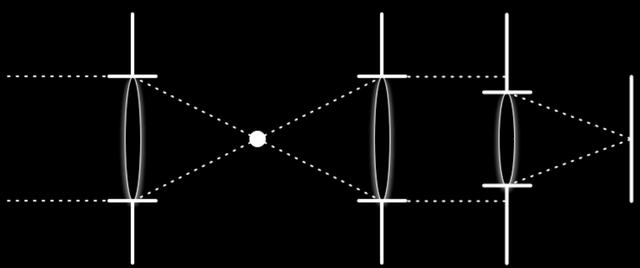

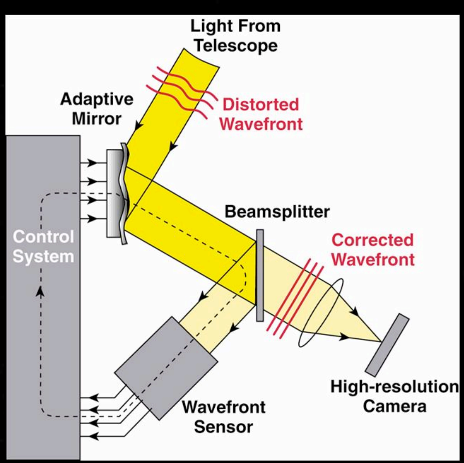

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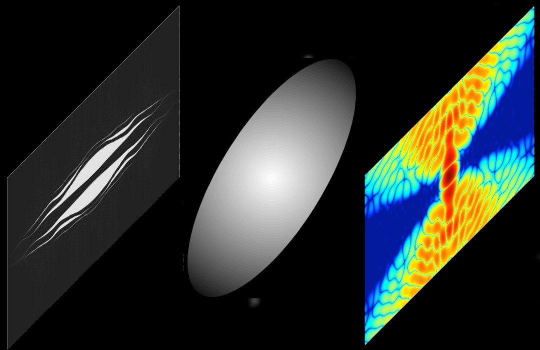

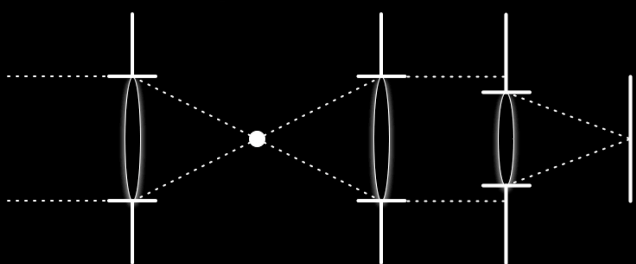

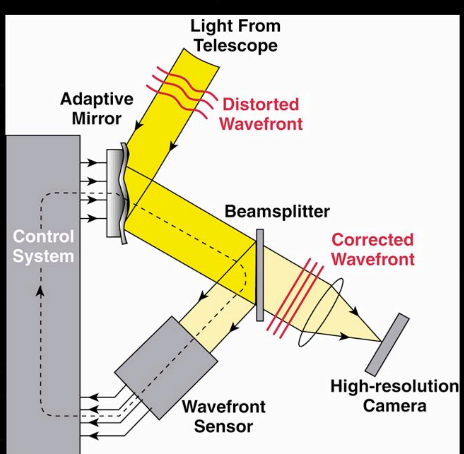

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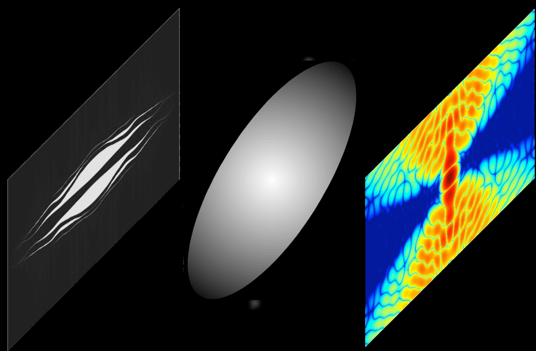
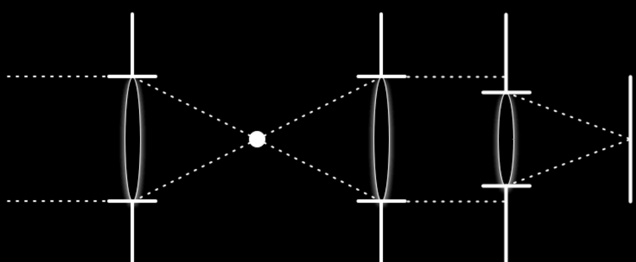
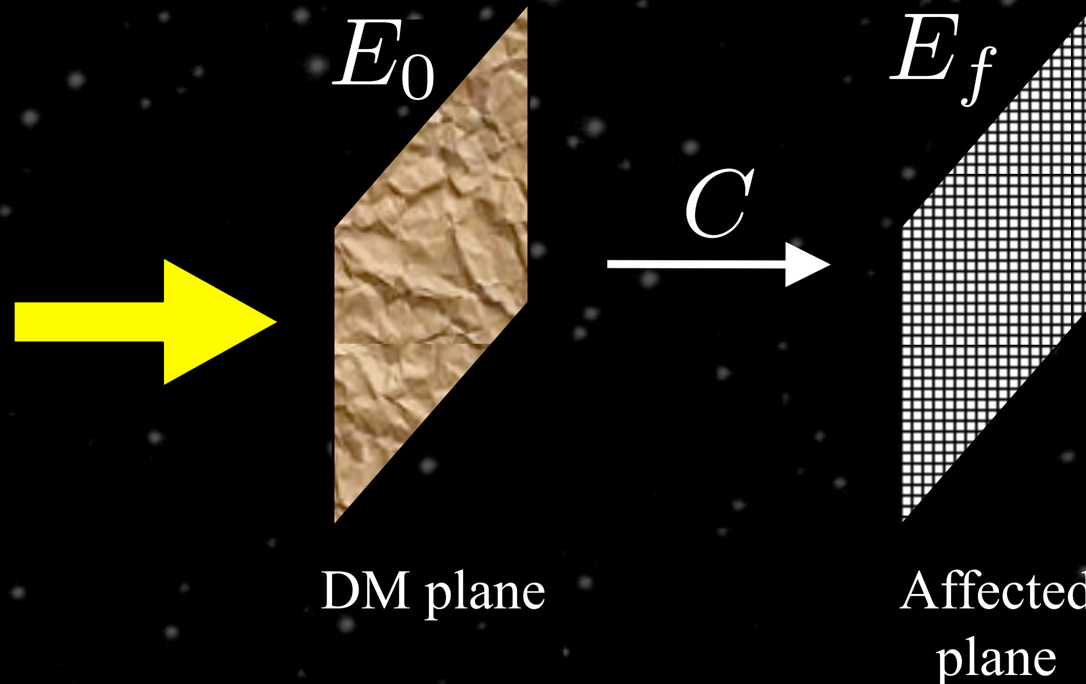
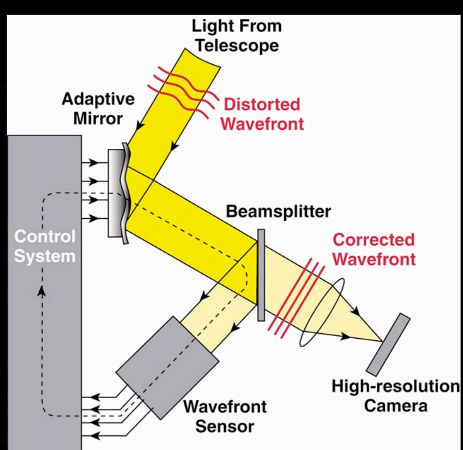






$$E_f = C\left\{E_0\right\}$$



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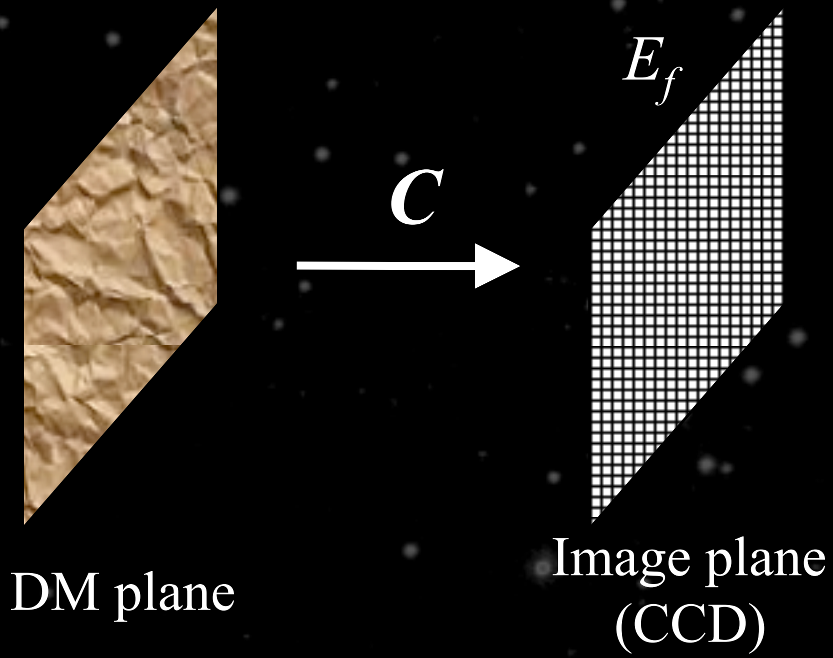
Electric Field Conjugation



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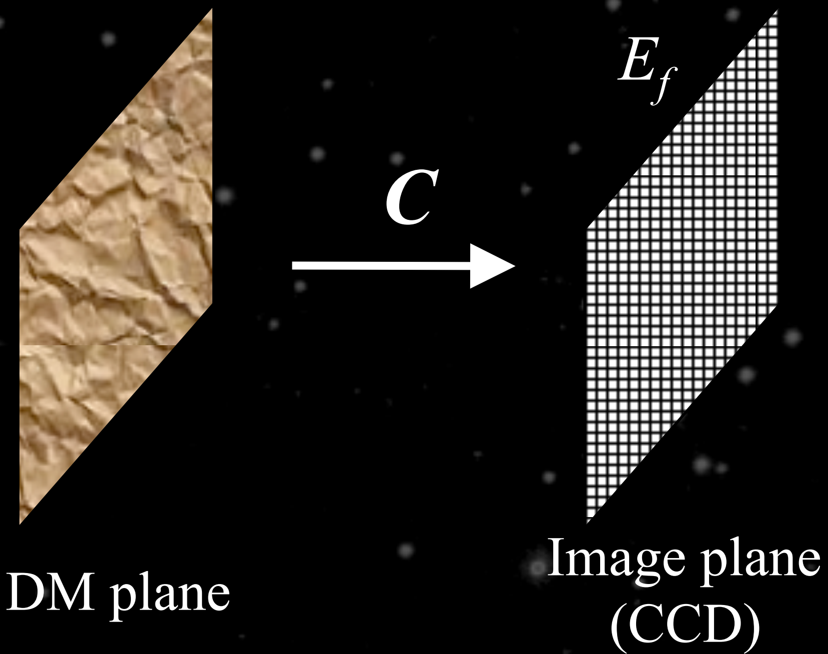
Electric Field Conjugation



$$
\begin{aligned}
E_f &= C\left\{Ae^{\alpha+i\beta}e^{i\psi}\right\} \\
&\approx C\left\{Ae^{\alpha+i\beta}\right\} + iC\left\{A\psi\right\} \\
&= E_{ab} + iC\left\{A\psi\right\}
\end{aligned}
$$

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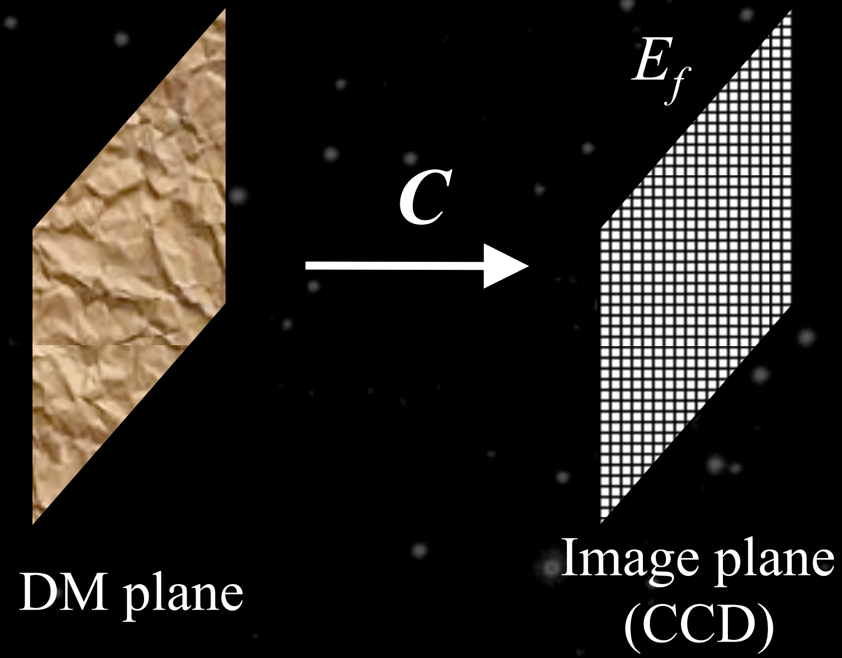

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Assuming the effect of the DM can be modeled as the sum of the effects of the individual influence functions:

$$C\left\{A\psi\right\} = G\bar{a}$$

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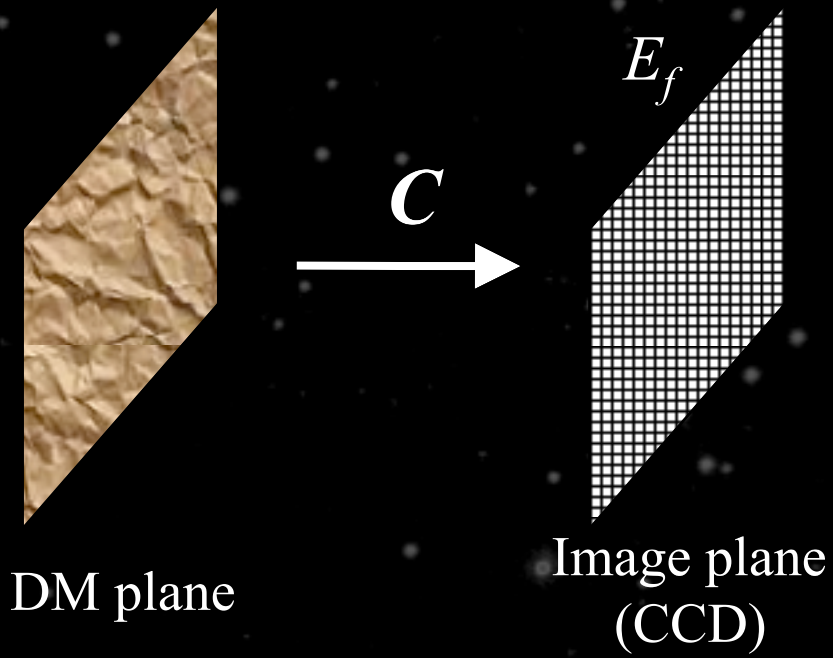
Electric Field Conjugation



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Assuming the effect of the DM can be modeled as the sum of the effects of the individual influence functions:

$$C\left\{A\psi\right\} = G\bar{a}$$

Then, in order to null the electric field in the image plane with the DM:

$$\boxed{G\bar{a} = iE_{ab}}$$

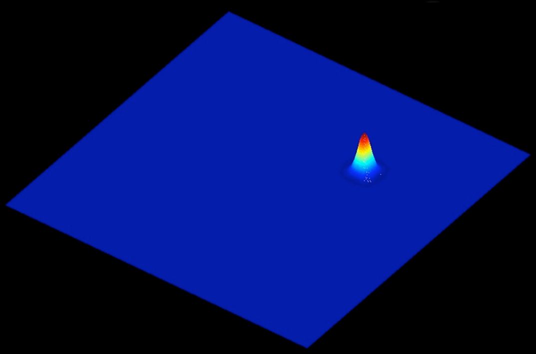
Electric Field Conjugation

What is this G matrix?

Electric Field Conjugation

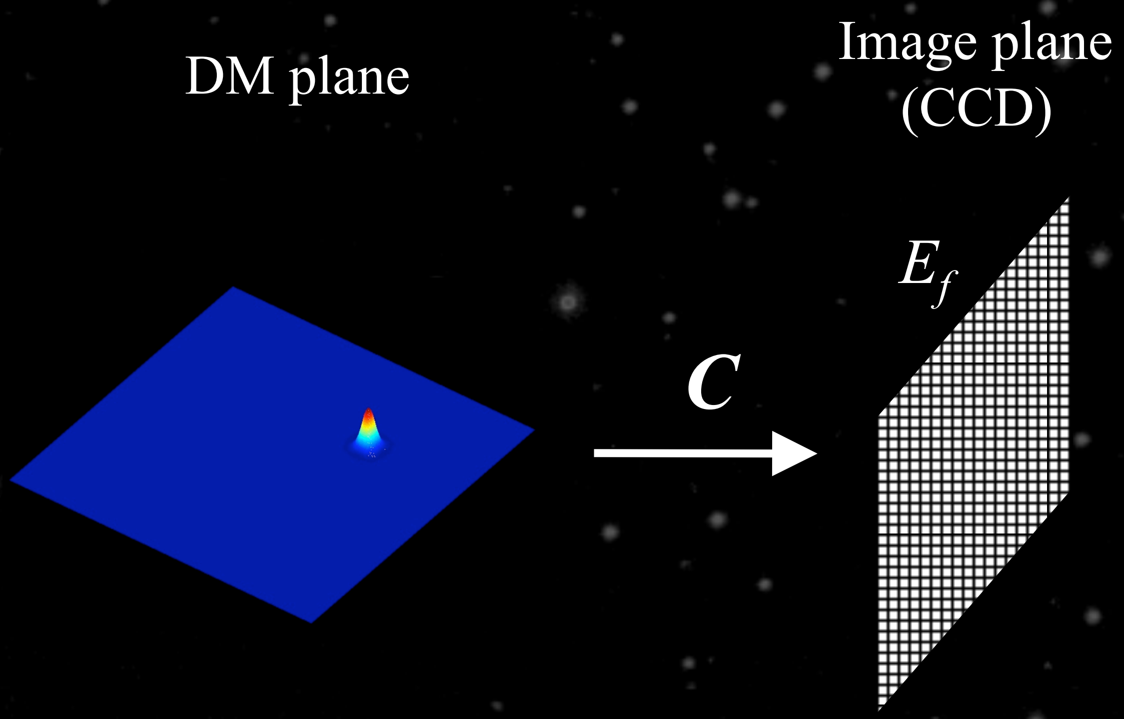
What is this G matrix?

DM plane



Electric Field Conjugation

What is this *G* matrix?



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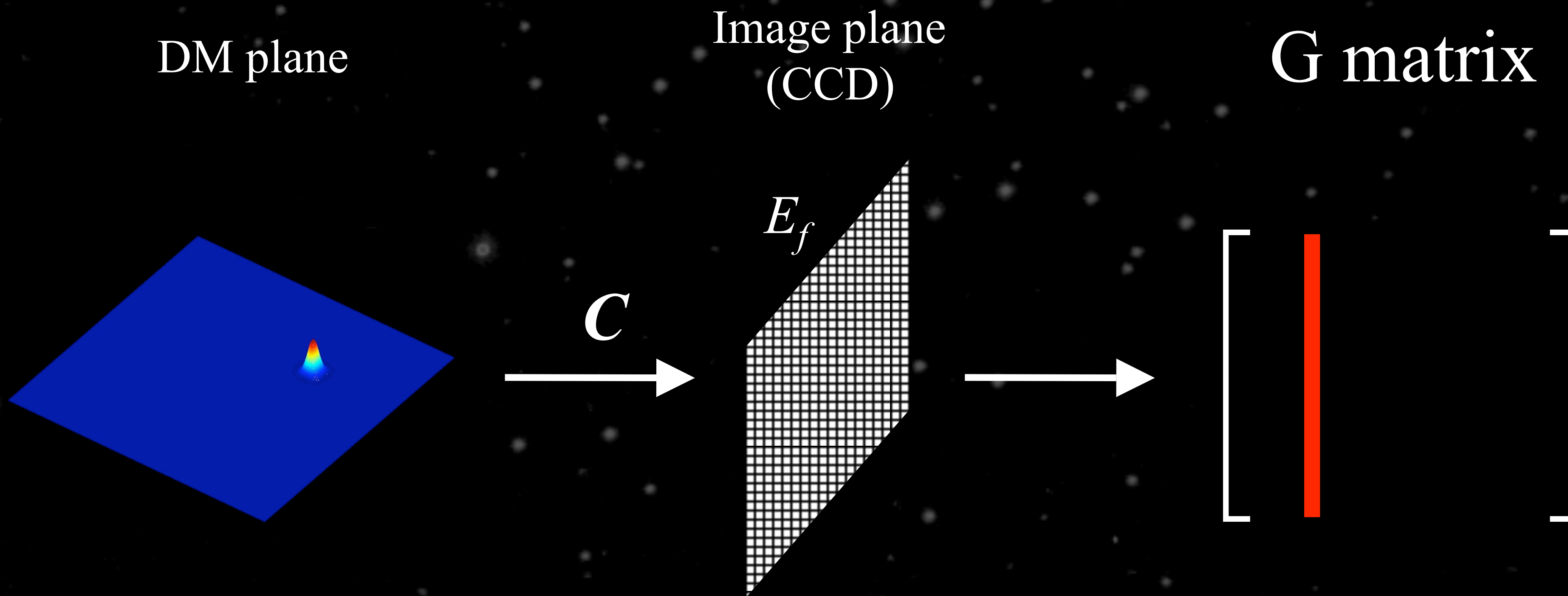

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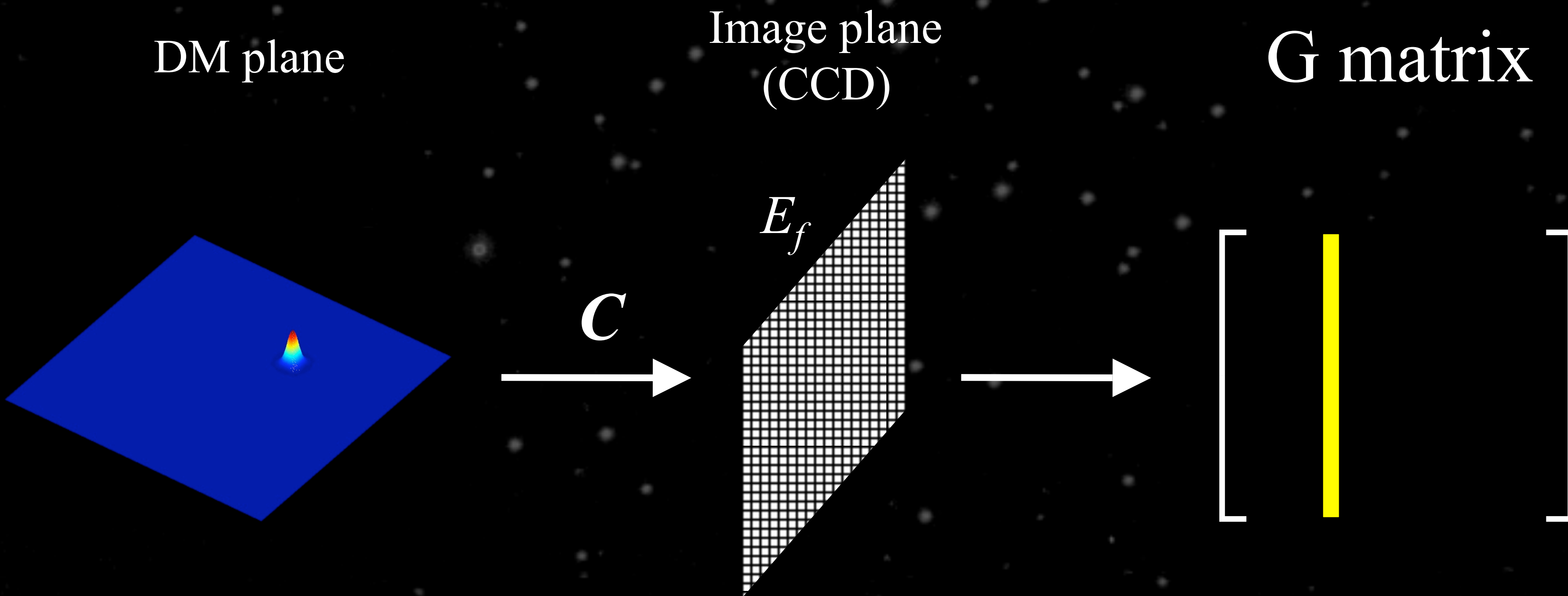

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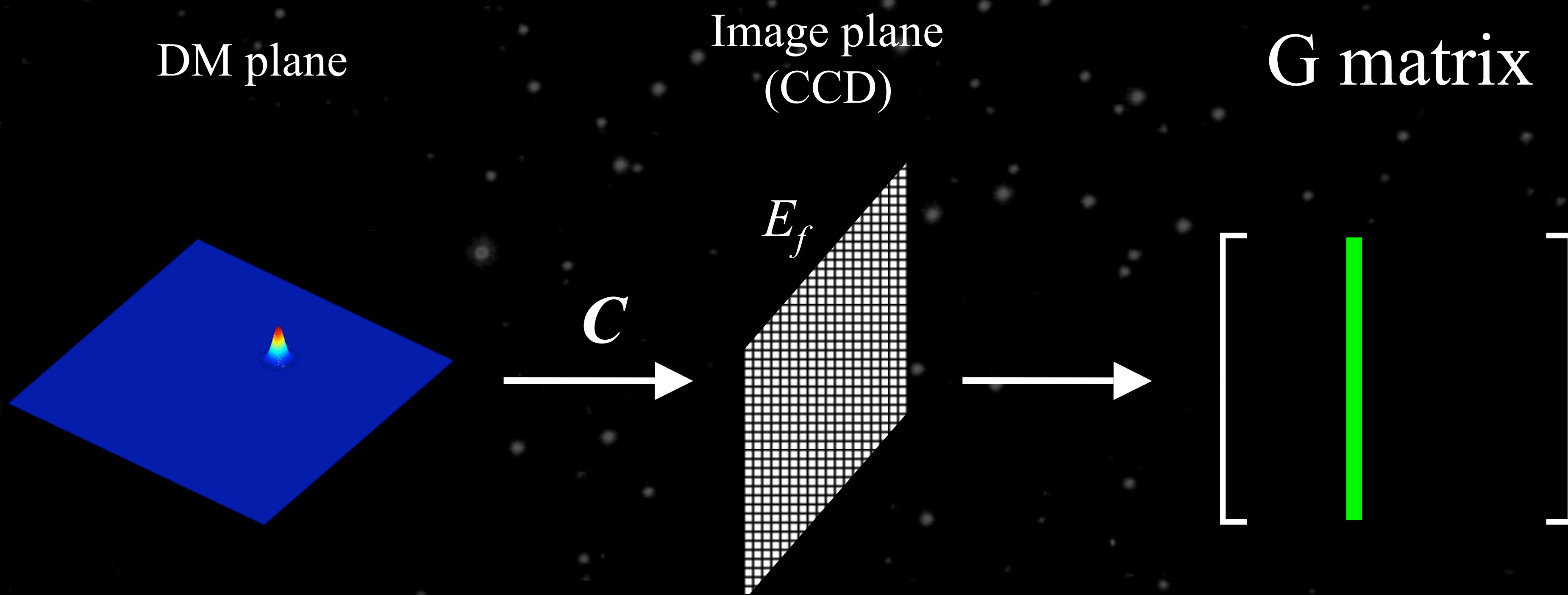

Electric Field Conjugation

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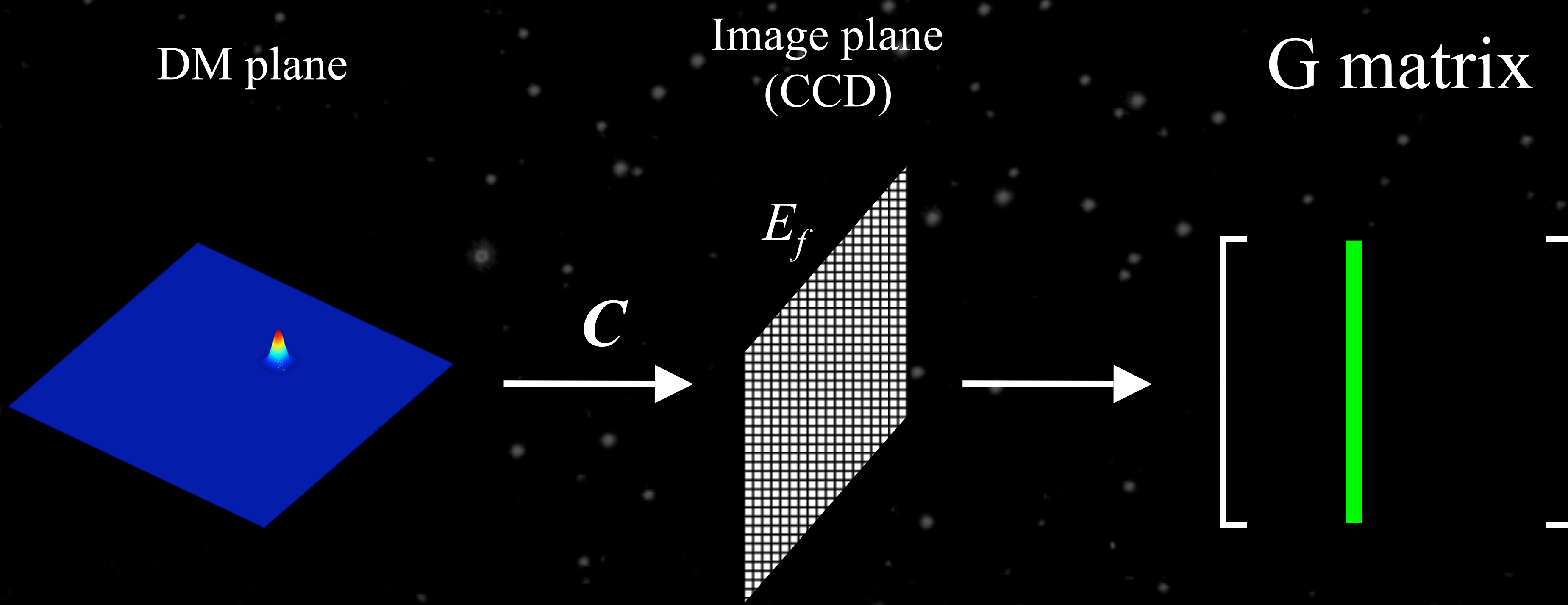

The main assumption in this method is that the overall effect of the DM in the image plane is the sum of the effects of each of the actuators

Electric Field Conjugation

Solving $G\bar{a} = iE_{ab}$

Electric Field Conjugation

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complex valued

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Problem: $\bar{a}$ must be real valued.

Electric Field Conjugation

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complex valued

Problem: $\bar{a}$ must be real valued.

Solution:

$$\bar{a} = \begin{bmatrix} \Re\{G\} \\ \cdots \\ \Im\{G\} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \end{bmatrix}$$

Interpretation:

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|E_{ab} + iG\bar{a}\|^2$$

Electric Field Conjugation

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This is the total energy in the region of interest!

Also related to energy minimization, Borde and Traub (2006)

Electric Field Conjugation

(Extensions)

Extension 1: Image plane pixels weighting

$$G\bar{a} = iE_{ab}$$

Electric Field Conjugation

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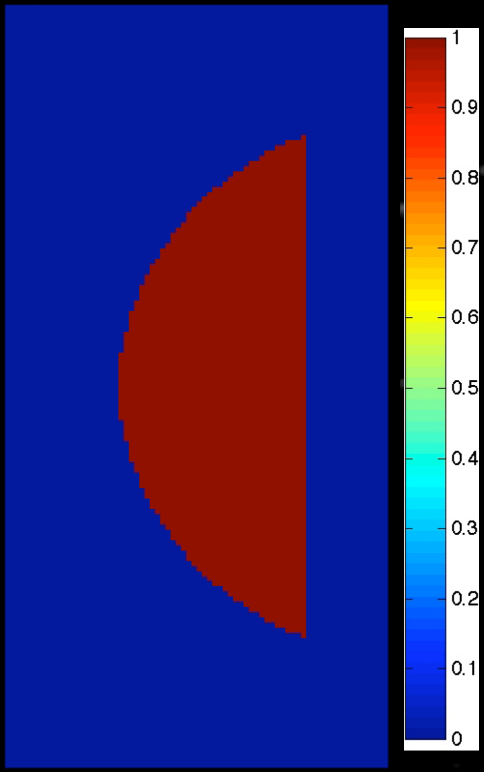

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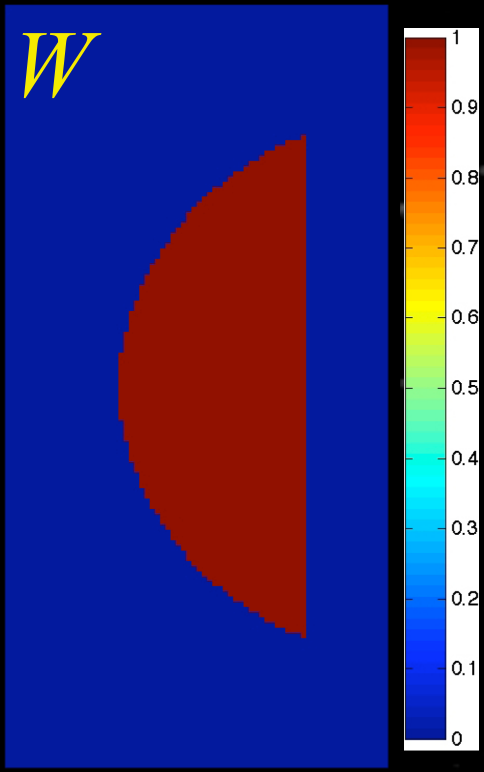
Electric Field Conjugation

(Extensions)

Extension 1: Image plane pixels weighting

$$W G \bar{a} = i W E_{ab}$$



Electric Field Conjugation

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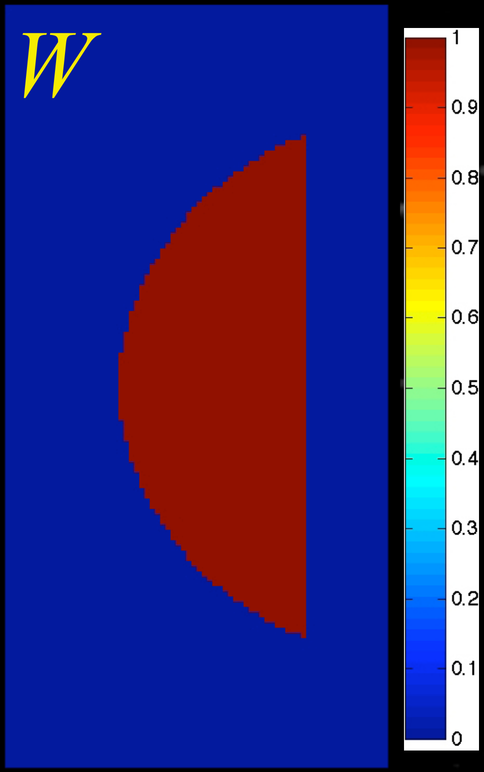

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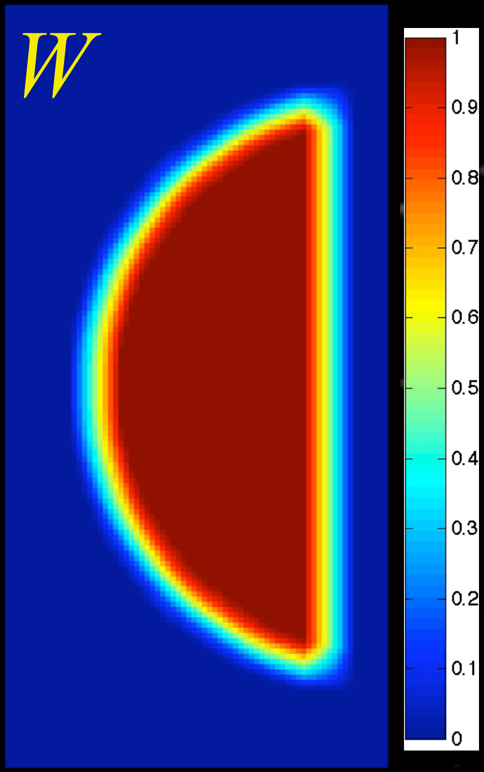

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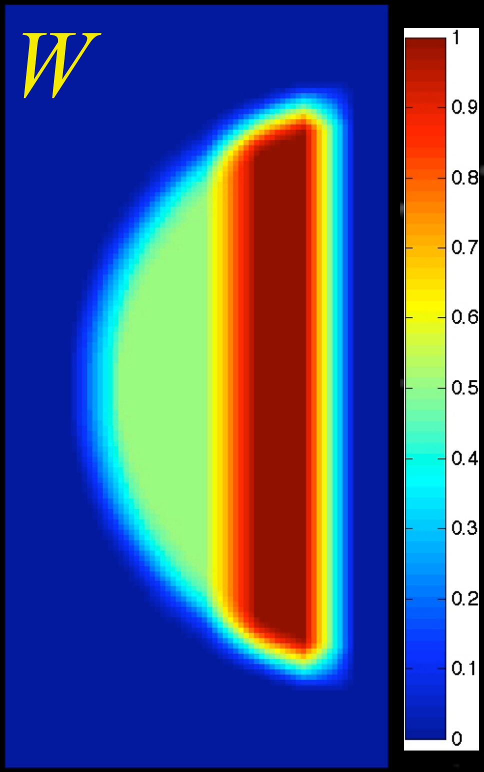

Electric Field Conjugation

(Extensions)

Extension 1: Image plane pixels weighting

$$W G \bar{a} = i W E_{ab}$$

If the system model is reduced to a single Fourier transform of an infinite aperture and the weighting function W reduces to isolated pixels that change their location according to the brightest peaks in the region of interest, then EFC becomes speckle nulling.

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Electric Field Conjugation

(Extensions)

Extension 2: Actuator regularization (Tikhonov regularization)

$$\bar{a} = \begin{bmatrix} \Re\{G\} \\ \cdots \\ \Im\{G\} \\ \\ \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \\ \\ \\ \\ \\ \end{bmatrix}$$

$$\bar{a}^* = \arg\min_{\bar{a} \in X} \left\| G\bar{a} + iE_{ab} \right\|^2$$

Electric Field Conjugation

(Extensions)

Extension 2: Actuator regularization (Tikhonov regularization)

$$\bar{a} = \begin{bmatrix} \Re\{G\} \\ \cdots \\ \Im\{G\} \\ \cdots \\ \mu \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \\ \cdots \\ \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \end{bmatrix}$$

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Electric Field Conjugation

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$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|G\bar{a} + iE_{ab}\|^2 + \mu^2 \|\bar{a}\|^2$$

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Electric Field Conjugation

(Extensions)

Extension 3: Multi wavelength correction

$$\bar{a} = \begin{bmatrix} \Re\{G \quad\quad\} \\ \Im\{G \quad\quad\} \\ \\ \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab} \quad\quad\} \\ \Im\{iE_{ab} \quad\quad\} \\ \\ \\ \\ \\ \end{bmatrix}$$

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \left\| G(\lambda_1)\bar{a} + iE_{ab}(\lambda_1) \right\|^2$$

Electric Field Conjugation

(Extensions)

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$$\bar{a} = \begin{bmatrix} \Re\{G(\lambda_1)\} \\ \Im\{G(\lambda_1)\} \\ \\ \\ \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}(\lambda_1)\} \\ \Im\{iE_{ab}(\lambda_1)\} \\ \\ \\ \\ \\ \\ \end{bmatrix}$$

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Electric Field Conjugation

(Extensions)

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$$\bar{a} = \begin{bmatrix} \Re\{G(\lambda_1)\} \\ \Im\{G(\lambda_1)\} \\ \Re\{G(\lambda_2)\} \\ \Im\{G(\lambda_2)\} \\ \vdots \\ \vdots \\ \Re\{G(\lambda_k)\} \\ \Im\{G(\lambda_k)\} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}(\lambda_1)\} \\ \Im\{iE_{ab}(\lambda_1)\} \\ \Re\{iE_{ab}(\lambda_2)\} \\ \Im\{iE_{ab}(\lambda_2)\} \\ \vdots \\ \vdots \\ \Re\{iE_{ab}(\lambda_k)\} \\ \Im\{iE_{ab}(\lambda_k)\} \end{bmatrix}$$

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(Extensions)

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$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|G(\lambda_1)\bar{a} + iE_{ab}(\lambda_1)\|^2 + \|G(\lambda_2)\bar{a} + iE_{ab}(\lambda_2)\|^2 + \cdots + \|G(\lambda_k)\bar{a} + iE_{ab}(\lambda_k)\|^2$$

Electric Field Conjugation

(Extensions)

Extension 4: Multiple DM correction

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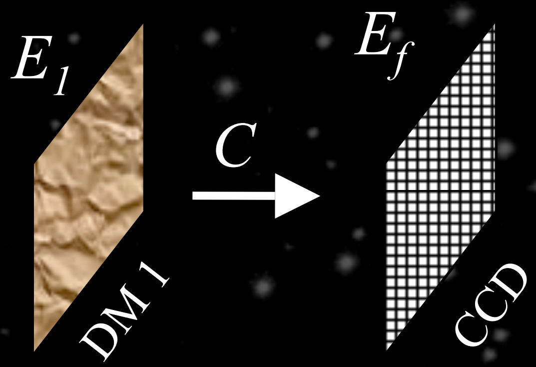
Electric Field Conjugation

(Extensions)

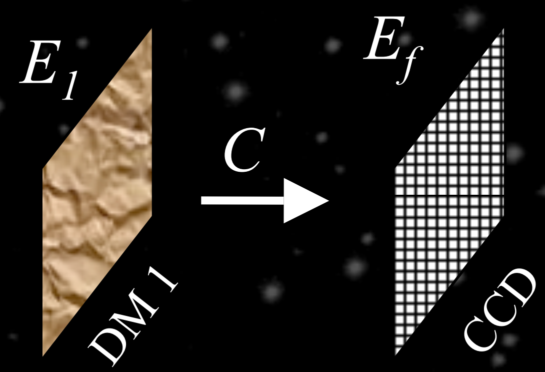
Extension 4: Multiple DM correction



Electric Field Conjugation

(Extensions)

Extension 4: Multiple DM correction



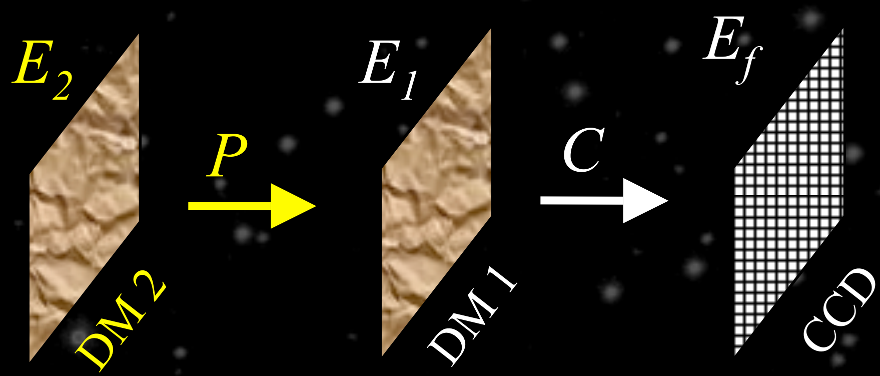
$$\begin{bmatrix} \bar{a}_1 \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{G_1\} & \\ \cdots & \\ \Im\{G_1\} & \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \end{bmatrix}$$

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|G_1\bar{a}_1 \qquad + E_{ab}\|^2$$

Electric Field Conjugation

(Extensions)

Extension 4: Multiple DM correction



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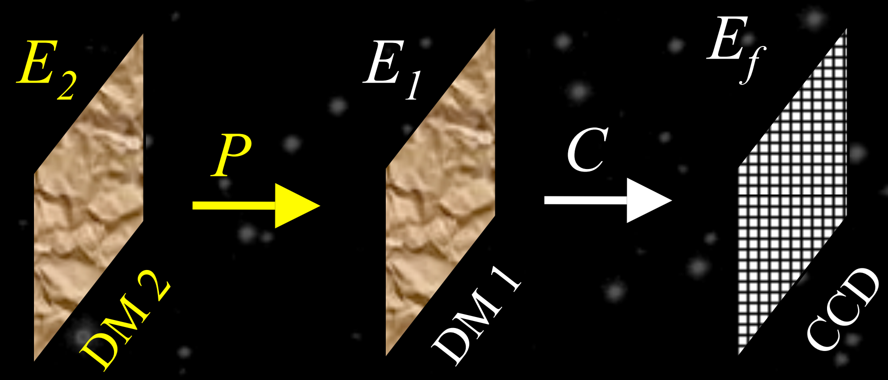
Electric Field Conjugation

(Extensions)

Extension 4: Multiple DM correction



$$\begin{bmatrix} \bar{a}_1 \\ \cdots \\ \bar{a}_2 \end{bmatrix} = \begin{bmatrix} \Re\{G_1\} & \Re\{G_2\} \\ \cdots & \cdots \\ \Im\{G_1\} & \Im\{G_2\} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \end{bmatrix}$$

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|G_1\bar{a}_1 + G_2\bar{a}_2 + E_{ab}\|^2$$

Electric Field Conjugation

(All extensions)

Basic EFC

$$\begin{bmatrix} \bar{a} \\ \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{ \quad G \quad \} \\ \dots \\ \Im\{ \quad G \quad \} \\ \\ \\ \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{i \quad E_{ab} \quad \} \\ \dots \\ \Im\{i \quad E_{ab} \quad \} \\ \\ \\ \\ \\ \end{bmatrix}$$

Electric Field Conjugation

(All extensions)

Image plane pixels weighting

$$\begin{bmatrix} \bar{a} \\ \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{WG \quad\quad\} \\ \cdots \\ \Im\{WG \quad\quad\} \\ \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iWE_{ab} \quad\quad\} \\ \cdots \\ \Im\{iWE_{ab} \quad\quad\} \\ \\ \\ \end{bmatrix}$$

Electric Field Conjugation

(All extensions)

Actuators regularization

$$\begin{bmatrix} \bar{a} \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{WG \quad\quad\} \\ \cdots \\ \Im\{WG \quad\quad\} \\ \\ \\ \cdots \\ \mu_1 \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iWE_{ab} \quad\quad\} \\ \cdots \\ \Im\{iWE_{ab} \quad\quad\} \\ \\ \\ \cdots \\ \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \end{bmatrix}$$

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Electric Field Conjugation

(All extensions)

Multi wavelength correction

$$\begin{bmatrix} \bar{a} \\ \\ \\ \end{bmatrix} = \begin{bmatrix} \Re\{WG\ (\lambda_1)\} \\ \cdots \\ \Im\{WG\ (\lambda_1)\} \\ \cdots \\ \Re\{WG\ (\lambda_2)\} \\ \cdots \\ \Im\{WG\ (\lambda_2)\} \\ \vdots \\ \Re\{WG\ (\lambda_k)\} \\ \cdots \\ \Im\{WG\ (\lambda_k)\} \\ \cdots \\ \mu_1 \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iWE_{ab}(\lambda_1)\} \\ \cdots \\ \Im\{iWE_{ab}(\lambda_1)\} \\ \cdots \\ \Re\{iWE_{ab}(\lambda_2)\} \\ \cdots \\ \Im\{iWE_{ab}(\lambda_2)\} \\ \vdots \\ \Re\{iWE_{ab}(\lambda_k)\} \\ \cdots \\ \Im\{iWE_{ab}(\lambda_k)\} \\ \cdots \\ \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix} \end{bmatrix}$$

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Electric Field Conjugation

(All extensions)

Multi DM correction

$$
\begin{bmatrix} \bar{a}_1 \\ \cdots \\ \bar{a}_2 \end{bmatrix} =
\begin{bmatrix}
\Re\{WG_1(\lambda_1)\} & \Re\{WG_2(\lambda_1)\} \\
\cdots & \cdots \\
\Im\{WG_1(\lambda_1)\} & \Im\{WG_2(\lambda_1)\} \\
\cdots & \cdots \\
\Re\{WG_1(\lambda_2)\} & \Re\{WG_2(\lambda_2)\} \\
\cdots & \cdots \\
\Im\{WG_1(\lambda_2)\} & \Im\{WG_2(\lambda_2)\} \\
\vdots & \vdots \\
\Re\{WG_1(\lambda_k)\} & \Re\{WG_2(\lambda_k)\} \\
\cdots & \cdots \\
\Im\{WG_1(\lambda_k)\} & \Im\{WG_2(\lambda_k)\} \\
\cdots & \cdots \\
\mu_1 \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} &
\mu_2 \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \ddots & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix}
\end{bmatrix}^{-1}
\begin{bmatrix}
\Re\{iWE_{ab}(\lambda_1)\} \\
\cdots \\
\Im\{iWE_{ab}(\lambda_1)\} \\
\cdots \\
\Re\{iWE_{ab}(\lambda_2)\} \\
\cdots \\
\Im\{iWE_{ab}(\lambda_2)\} \\
\vdots \\
\Re\{iWE_{ab}(\lambda_k)\} \\
\cdots \\
\Im\{iWE_{ab}(\lambda_k)\} \\
\cdots \\
\begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix}
\end{bmatrix}
$$

Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

$$E_f \approx E_{ab} + iC\left\{A\psi\right\}$$

Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

$$E_k \approx E_{ab} + iC\left\{A\psi_k\right\}$$

Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

$$E_k \approx E_{ab} + iC\{A\psi_k\}$$

$$\downarrow$$

$$I_k \approx \left|E_{ab} + iC\{A\psi_k\}\right|^2$$

Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

$$E_k \approx E_{ab} + iC\left\{A\psi_k\right\}$$

$$\downarrow$$

$$I_k \approx \left|E_{ab} + iC\left\{A\psi_k\right\}\right|^2$$

Suppose we deform the DM in pairs of shapes, ψ_k and $-\psi_k$, then,

Electric Field Conjugation

(The reconstruction stage)

The electric field at the science camera is approximated as:

$$E_k \approx E_{ab} + iC\left\{A\psi_k\right\}$$

$$\downarrow$$

$$I_k \approx \left|E_{ab} + iC\left\{A\psi_k\right\}\right|^2$$

Suppose we deform the DM in pairs of shapes, ψ_k and $-\psi_k$, then,

$$I_k^+ \approx \left|E_{ab} + iC\left\{A\psi_k\right\}\right|^2$$

$$I_k^- \approx \left|E_{ab} - iC\left\{A\psi_k\right\}\right|^2$$

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Electric Field Conjugation

(The reconstruction stage)

If we take the difference between those images...

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Electric Field Conjugation

(The reconstruction stage)

If we take the difference between those images...

$$I_k^+ - I_k^- = 2\overline{E_{ab}}C\left\{A\psi_k\right\} + 2E_{ab}\overline{C\left\{A\psi_k\right\}}$$

Electric Field Conjugation

(The reconstruction stage)

If we take the difference between those images...

$$I_k^+ - I_k^- = 2\overline{E_{ab}}C\left\{A\psi_k\right\} + 2E_{ab}\overline{C\left\{A\psi_k\right\}}$$

If we take more pairs and stack them up...

$$\begin{bmatrix} I_1^+ - I_1^- \\ \vdots \\ I_k^+ - I_k^- \end{bmatrix} = \frac{1}{4}\begin{bmatrix} \Re\left\{C\left\{A\psi_1\right\}\right\} & \Im\left\{C\left\{A\psi_1\right\}\right\} \\ \vdots & \vdots \\ \Re\left\{C\left\{A\psi_k\right\}\right\} & \Im\left\{C\left\{A\psi_k\right\}\right\} \end{bmatrix}\begin{bmatrix} \Re\left\{E_{ab}\right\} \\ \Im\left\{E_{ab}\right\} \end{bmatrix}$$

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What shapes on the DM should we use for the probes?

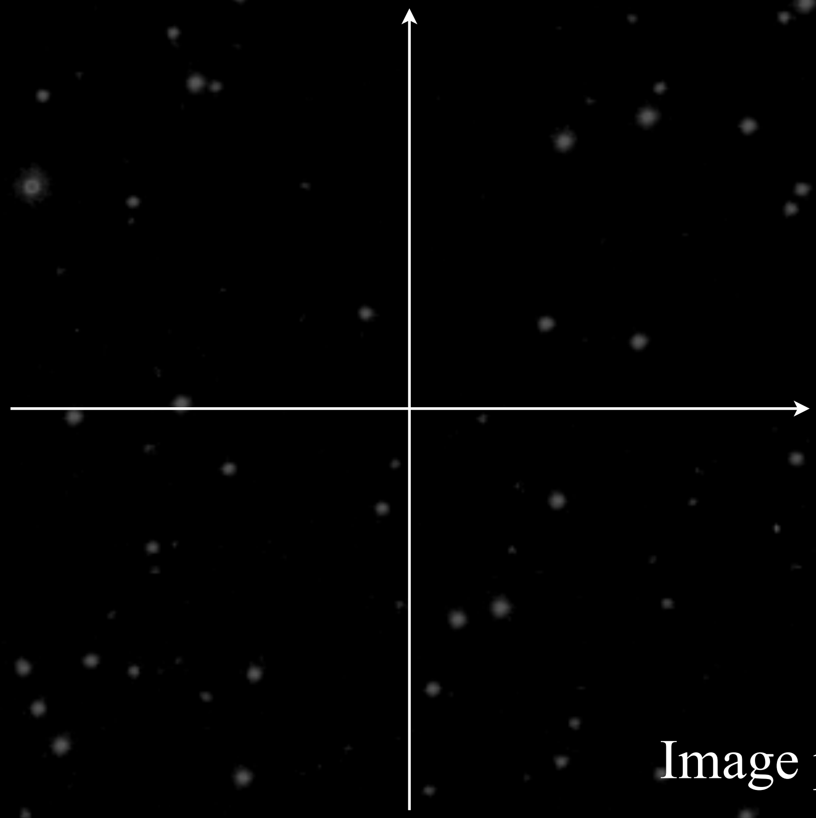

Image plane

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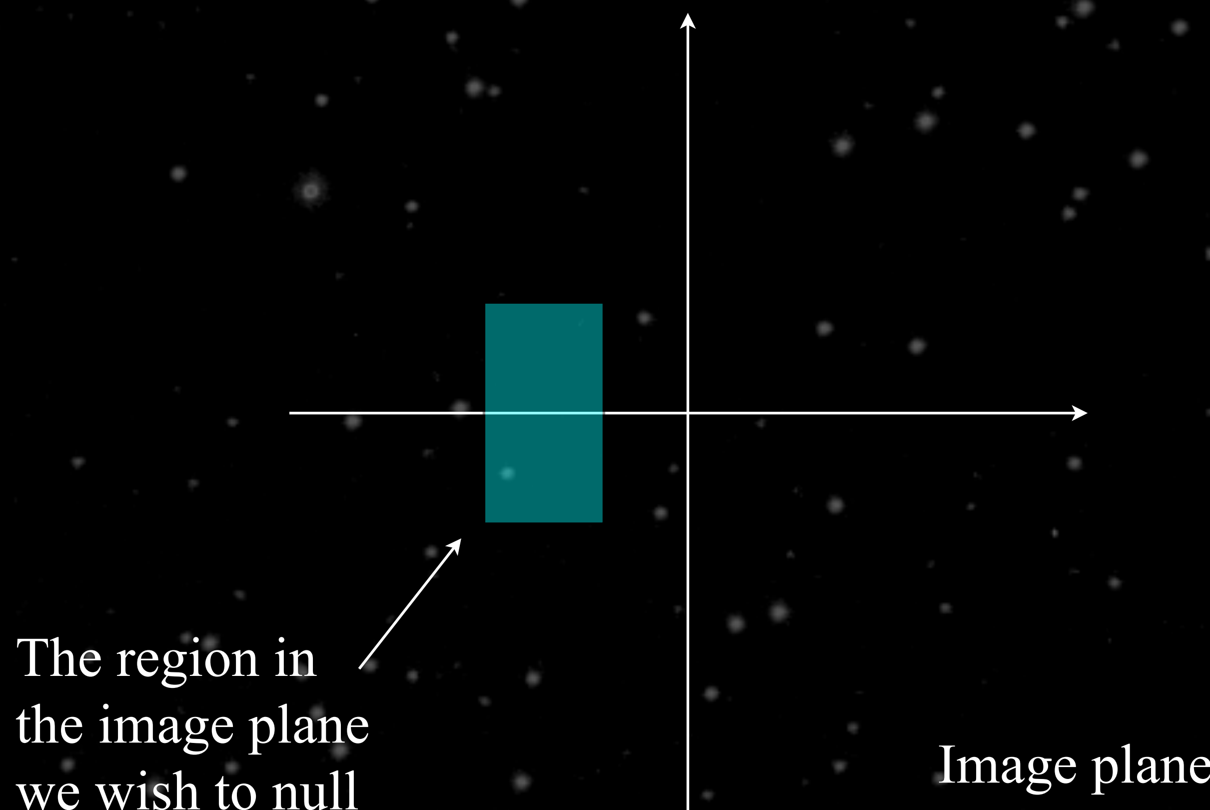
What shapes on the DM should we use for the probes?



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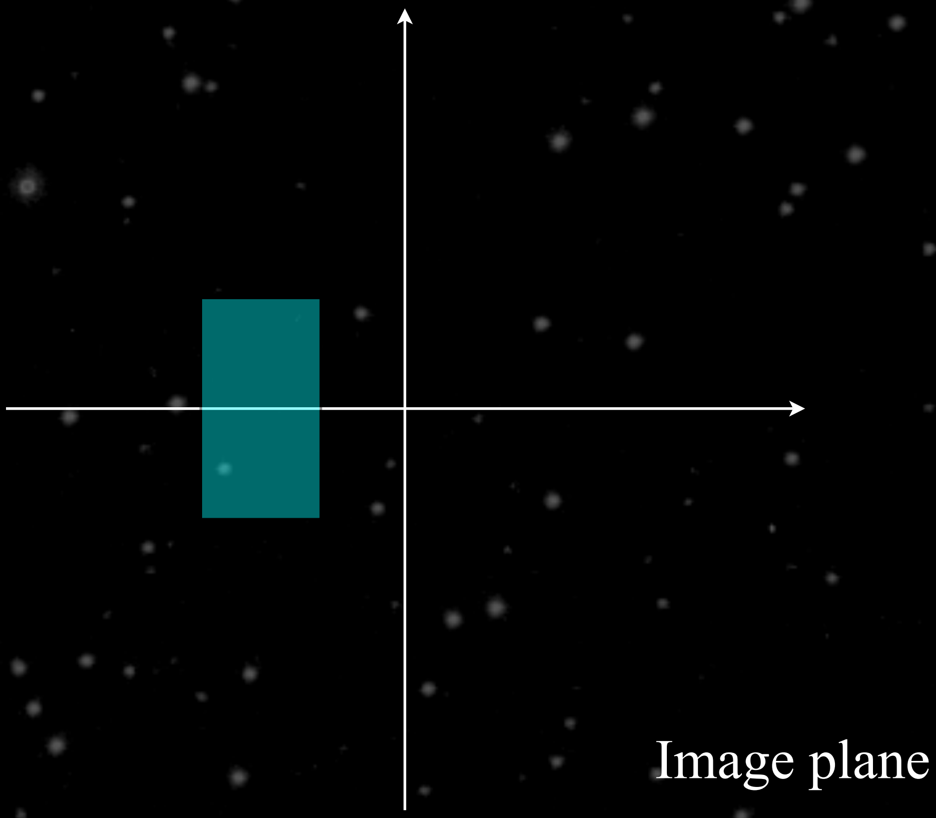
What shapes on the DM should we use for the probes?

$$DM(x, y) = \;?$$



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What shapes on the DM should we use for the probes?

$$DM(x,y) = sinc(w_x x)sinc(w_y y)$$

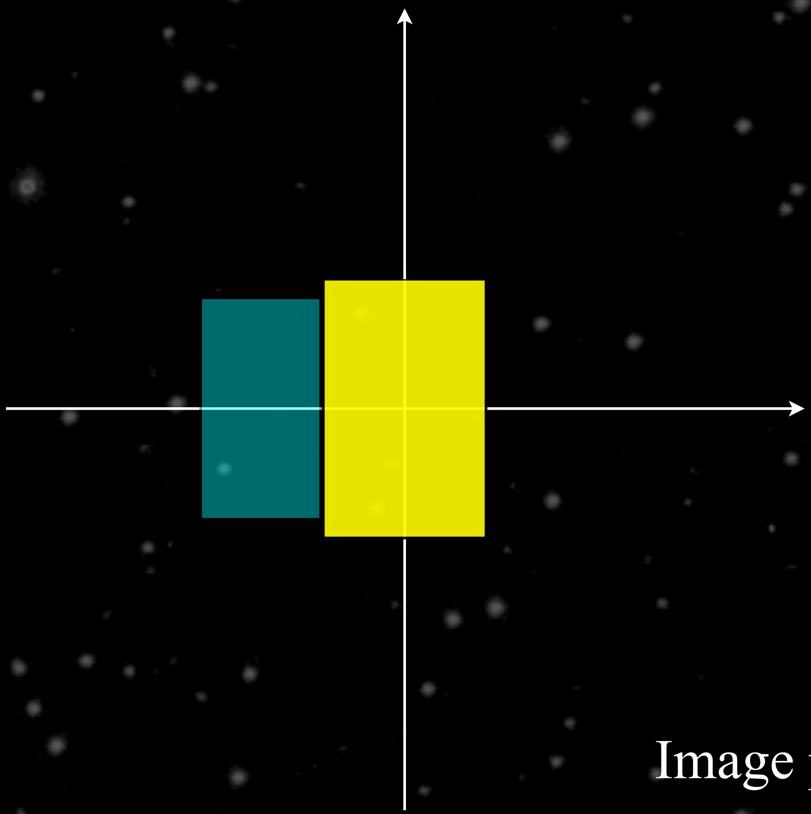
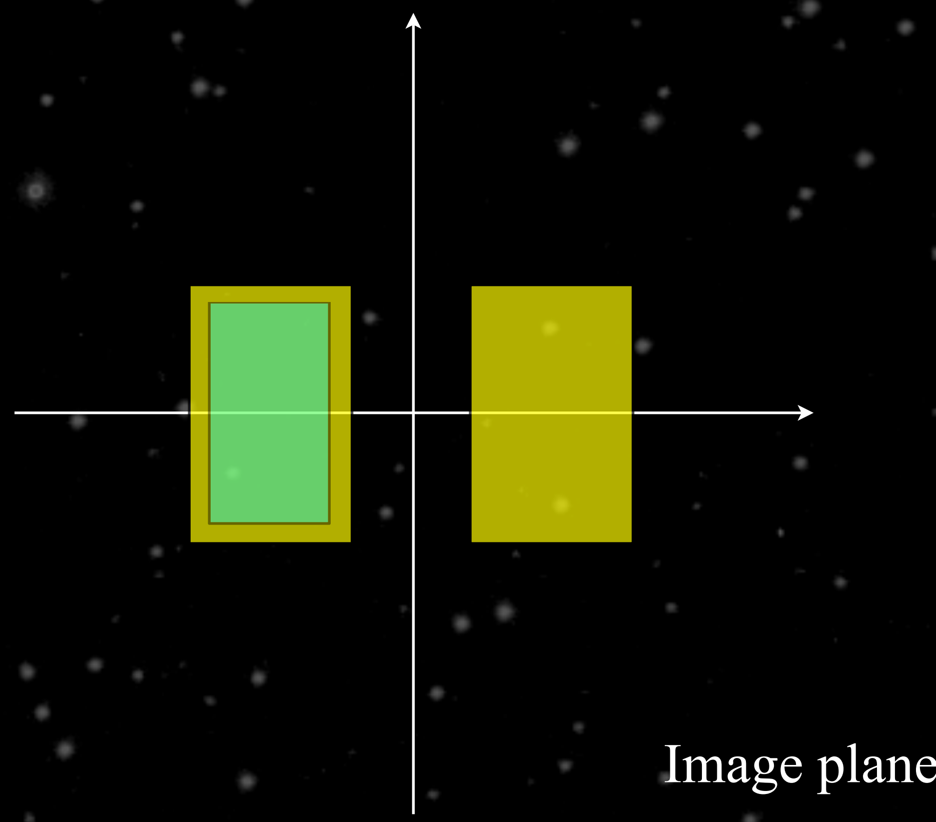


Image plane

What shapes on the DM should we use for the probes?

$$DM(x,y) = sinc(w_x x) sinc(w_y y) cos(f_x x + \phi)$$



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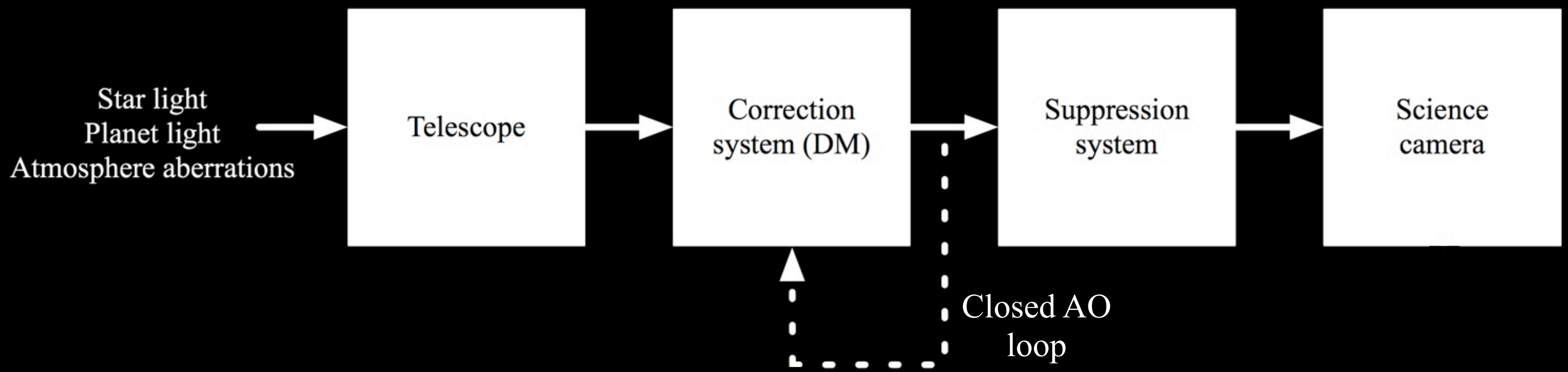
Can we all live in peace?



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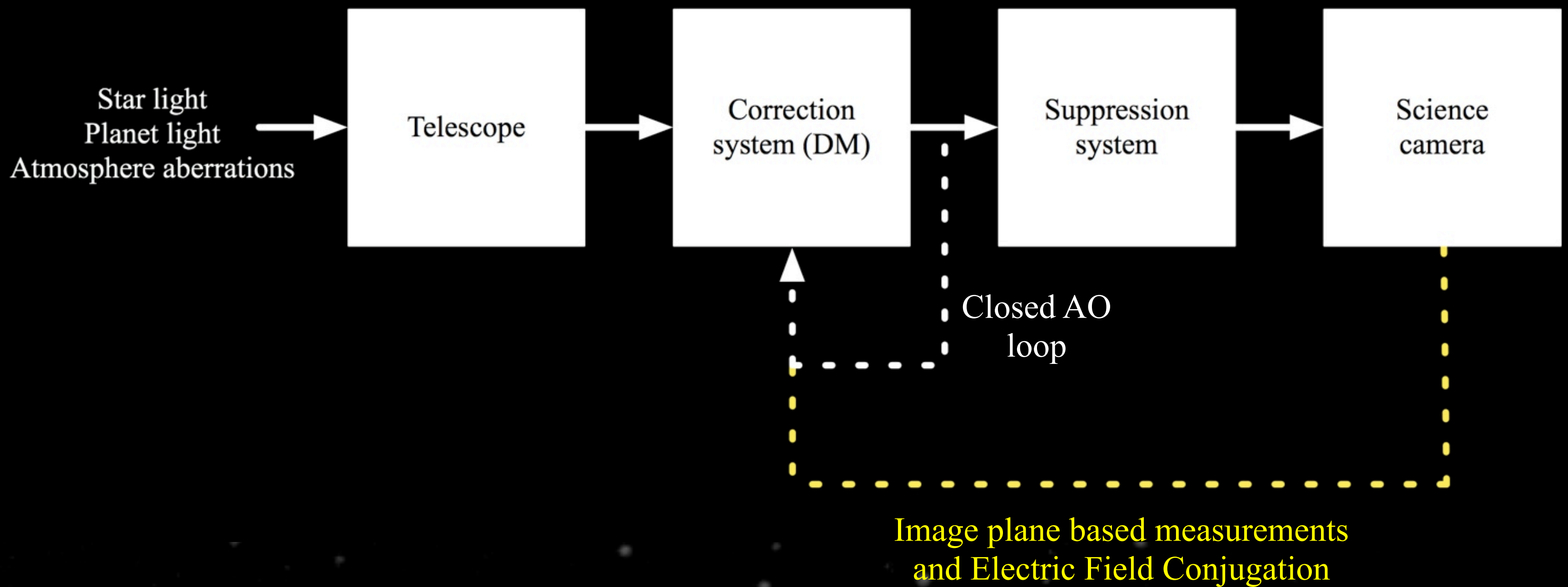
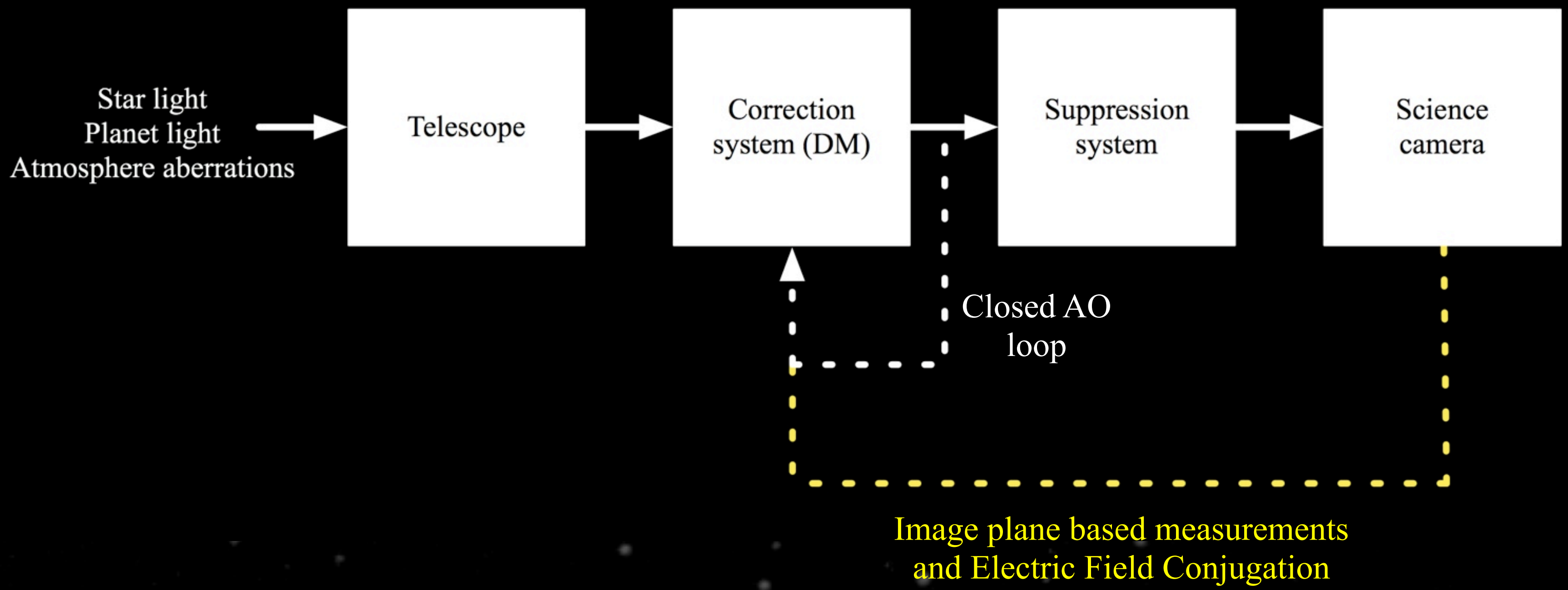
Can we all live in peace?



Can we all live in peace?



Experiments have started at Palomar to try and close the image plane based correction loop around the AO system.

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Electric Field Conjugation

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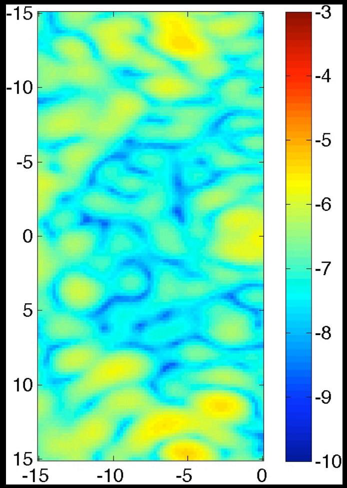
Electric Field Conjugation

Measured intensity



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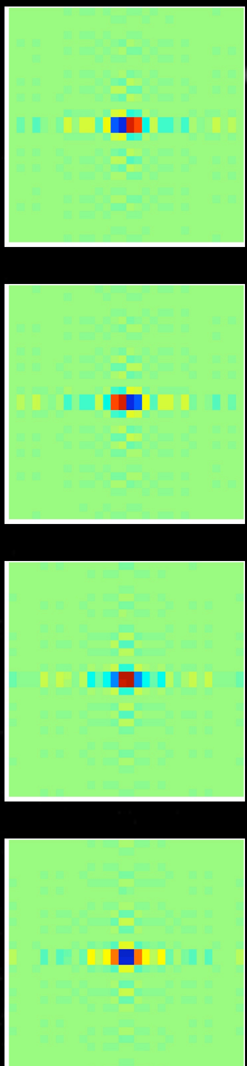
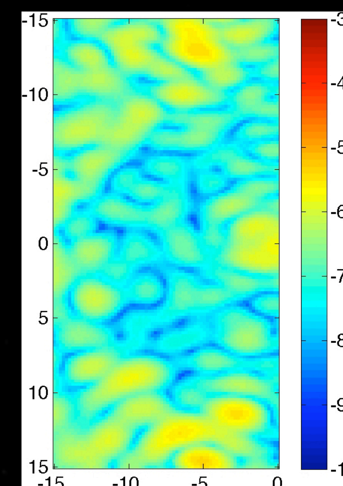
Electric Field Conjugation

DM voltages



Measured intensity



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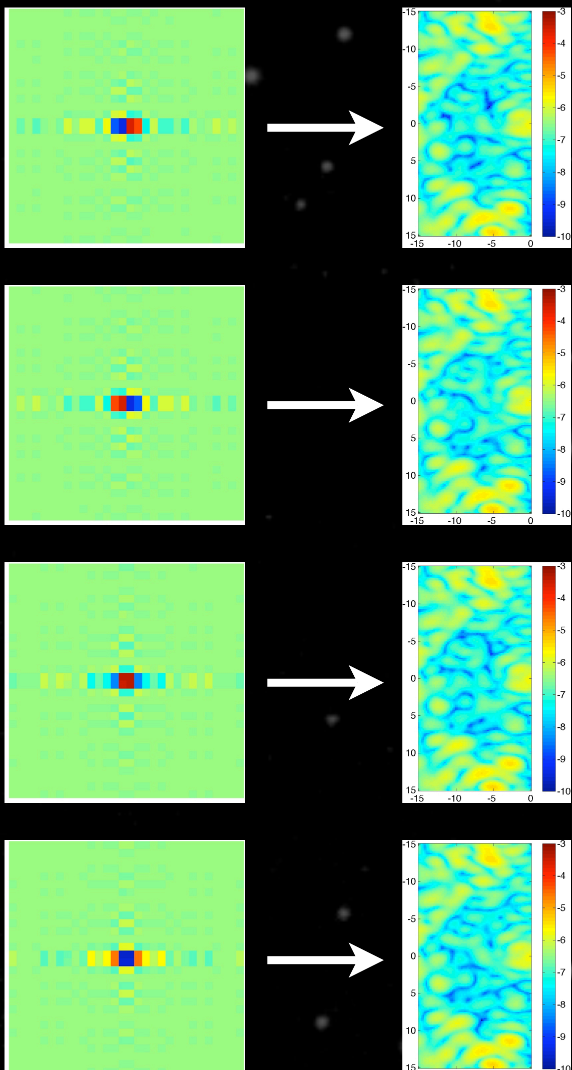
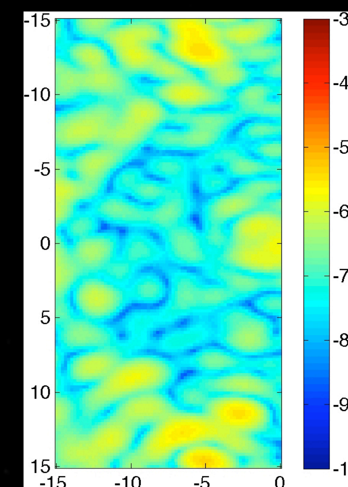
Electric Field Conjugation

DM voltages

Probe images



Measured intensity



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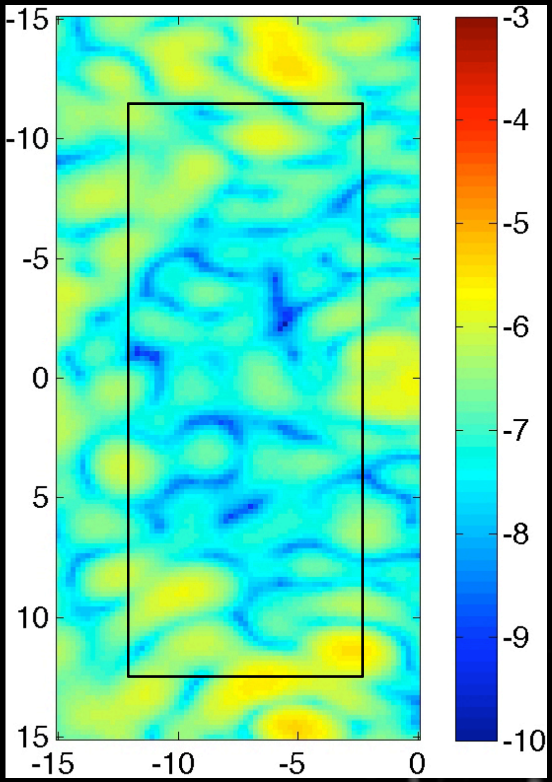
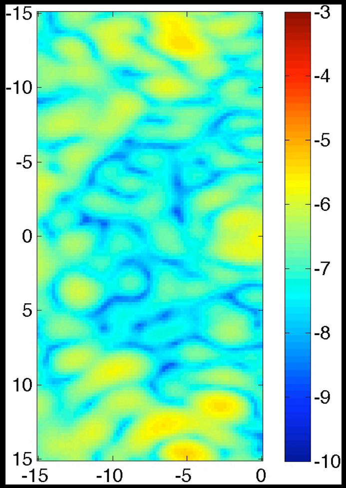
Electric Field Conjugation



Measured intensity



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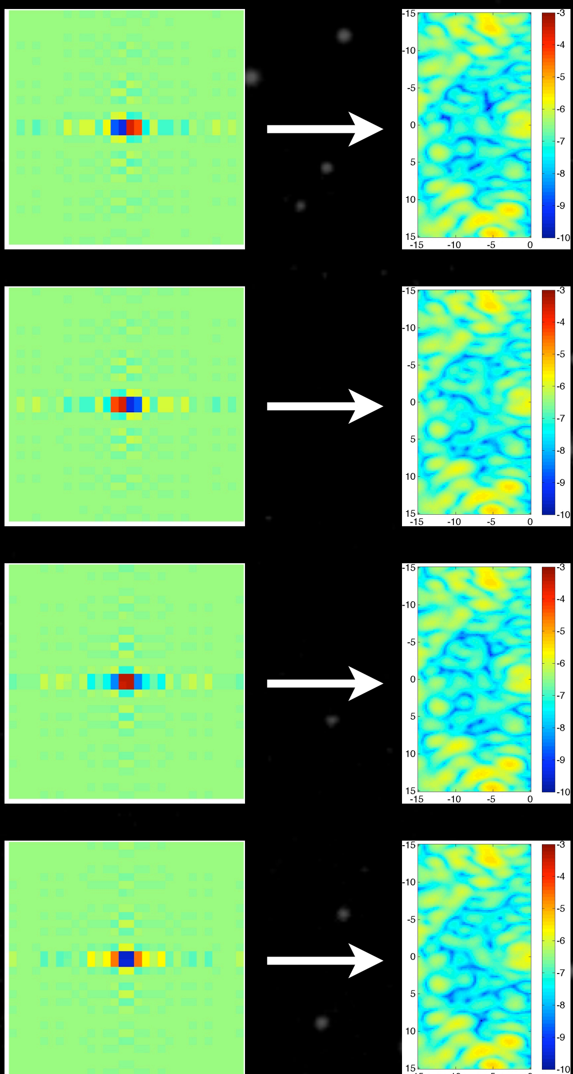
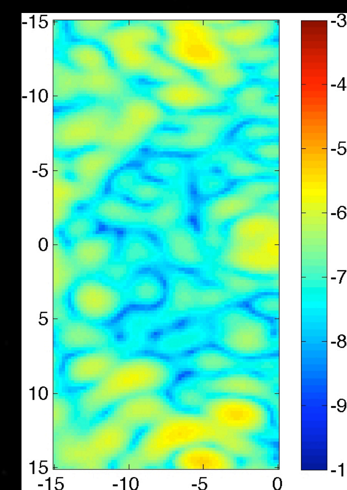
Electric Field Conjugation

DM voltages

Probe images



Measured intensity



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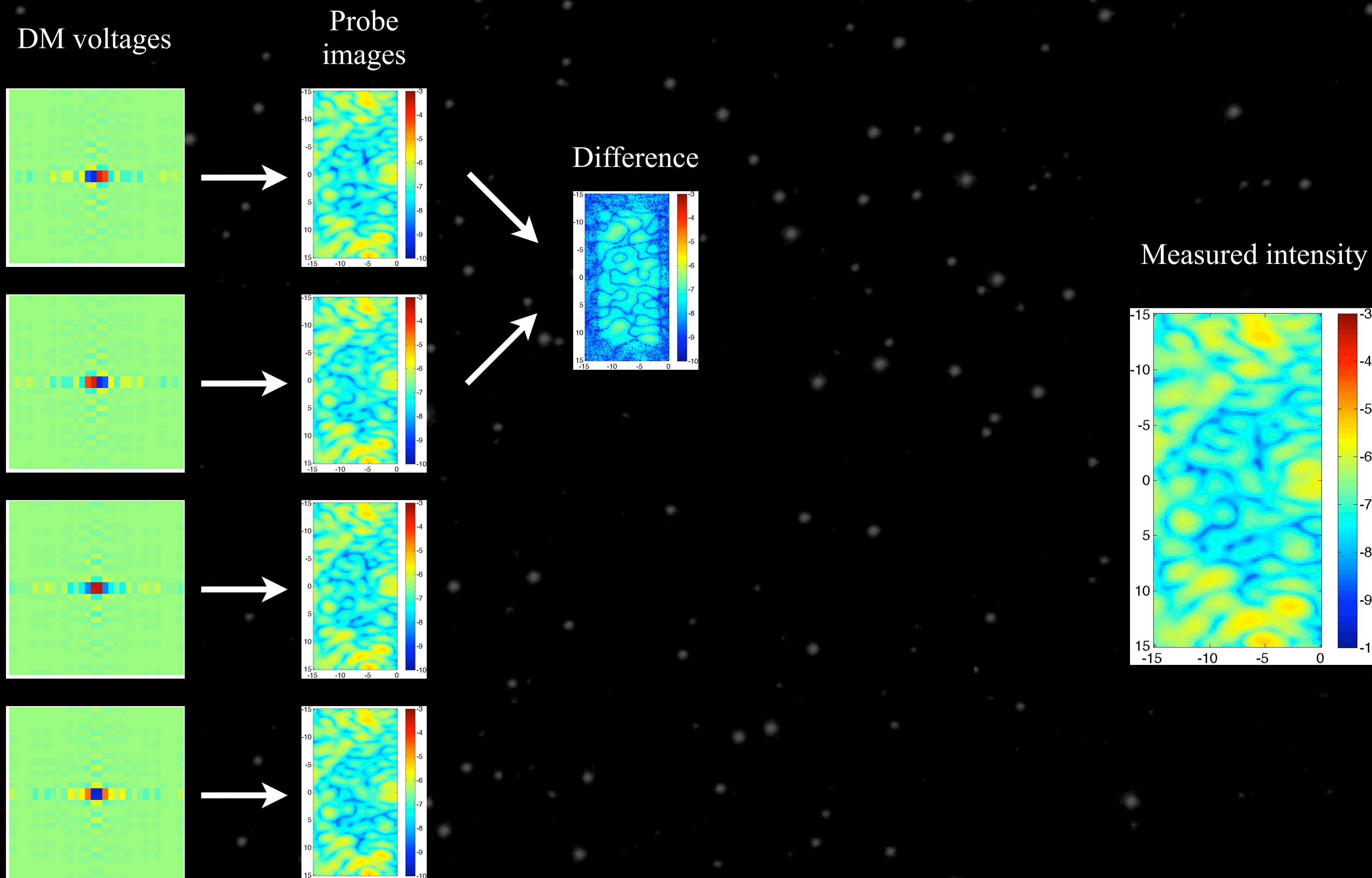
Electric Field Conjugation



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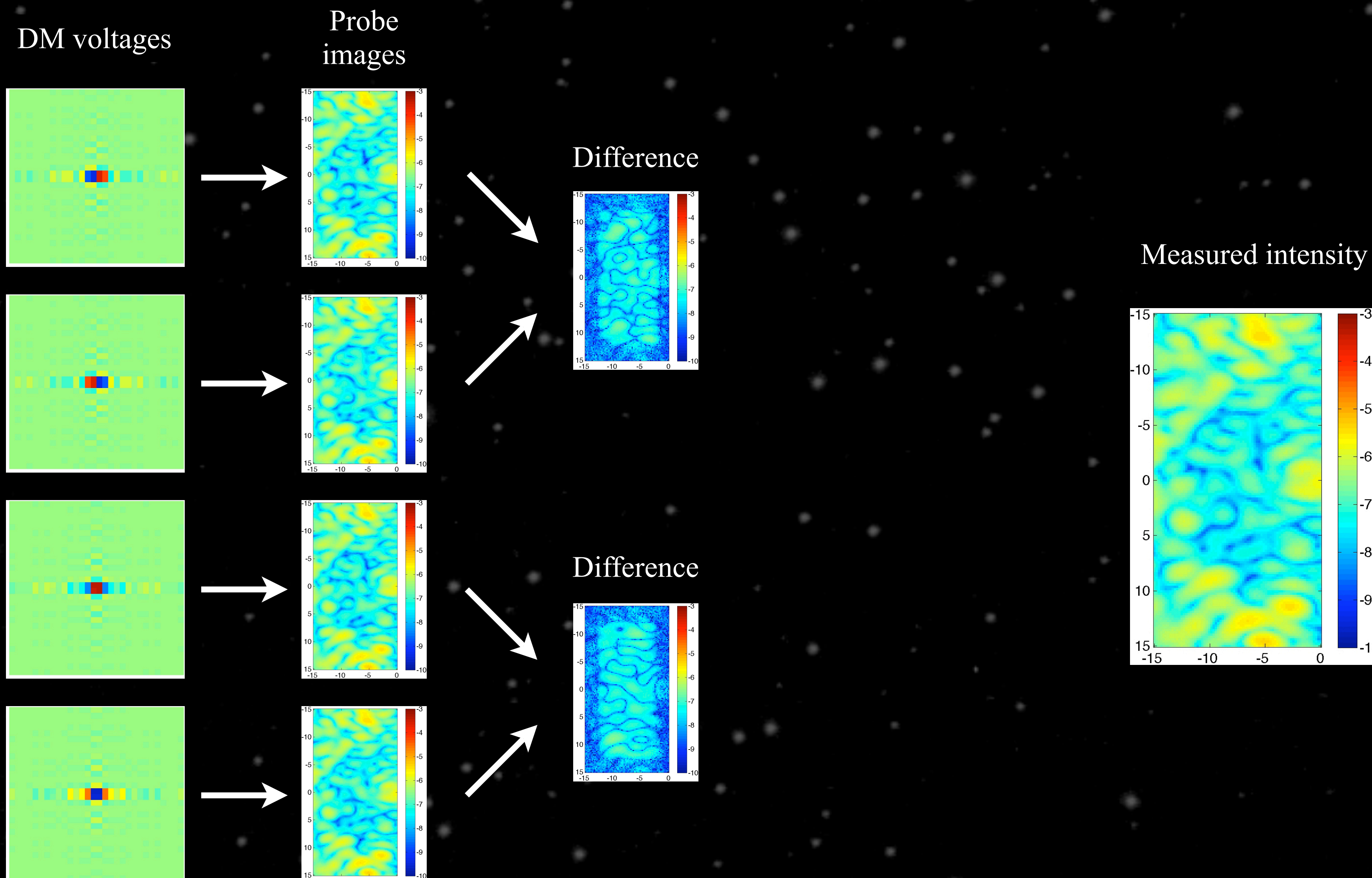
Electric Field Conjugation



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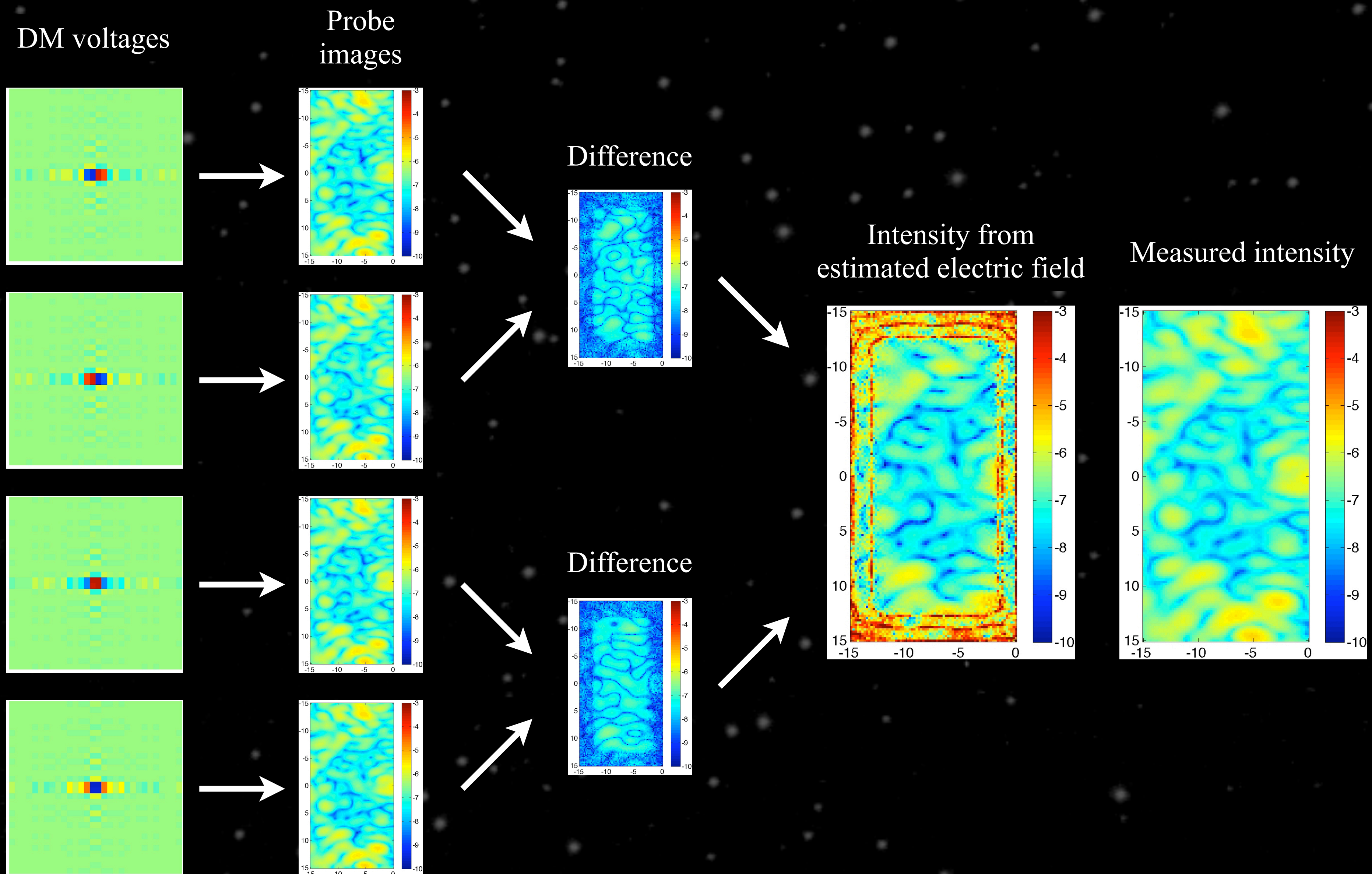
Electric Field Conjugation



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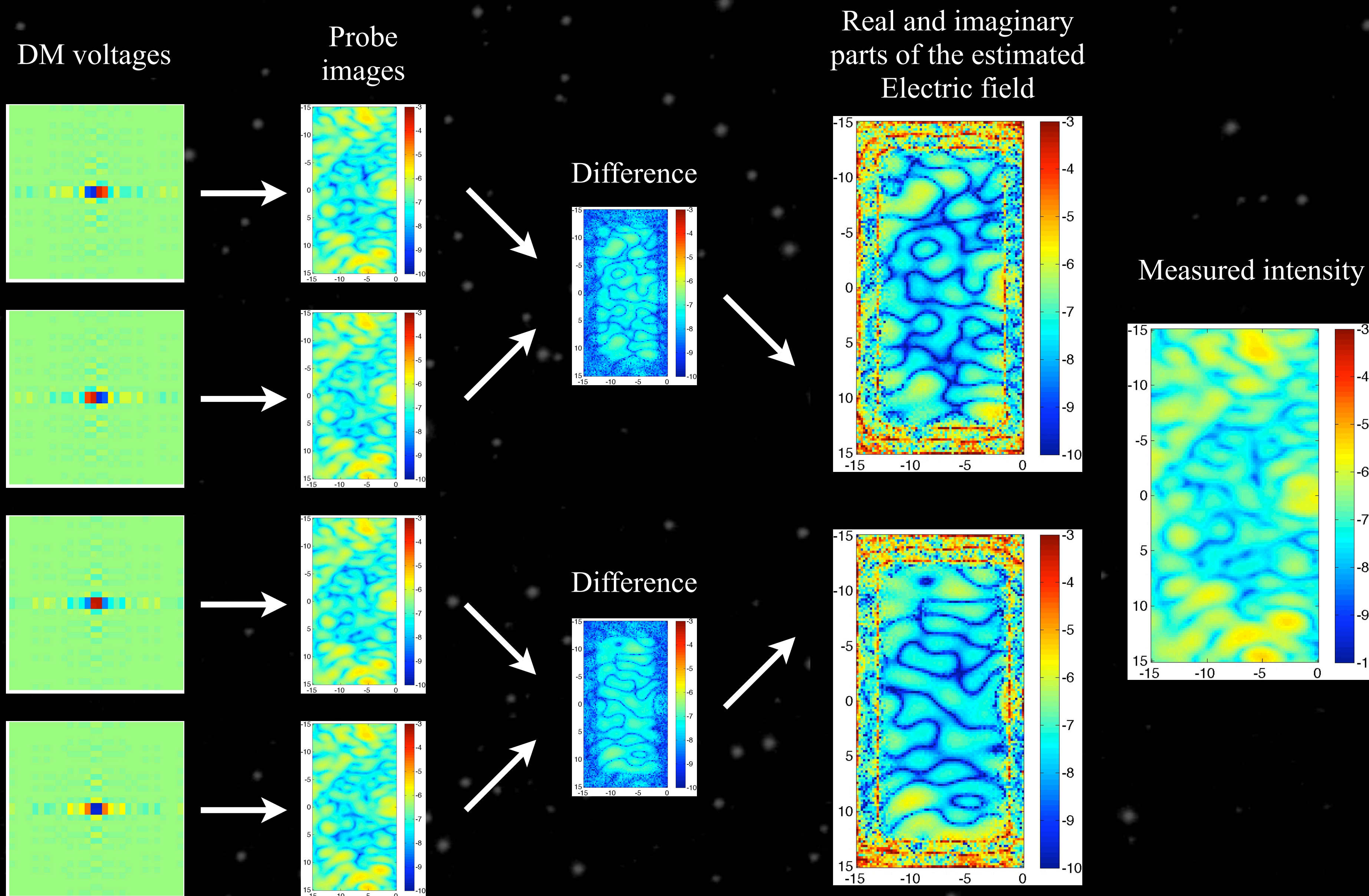
Electric Field Conjugation



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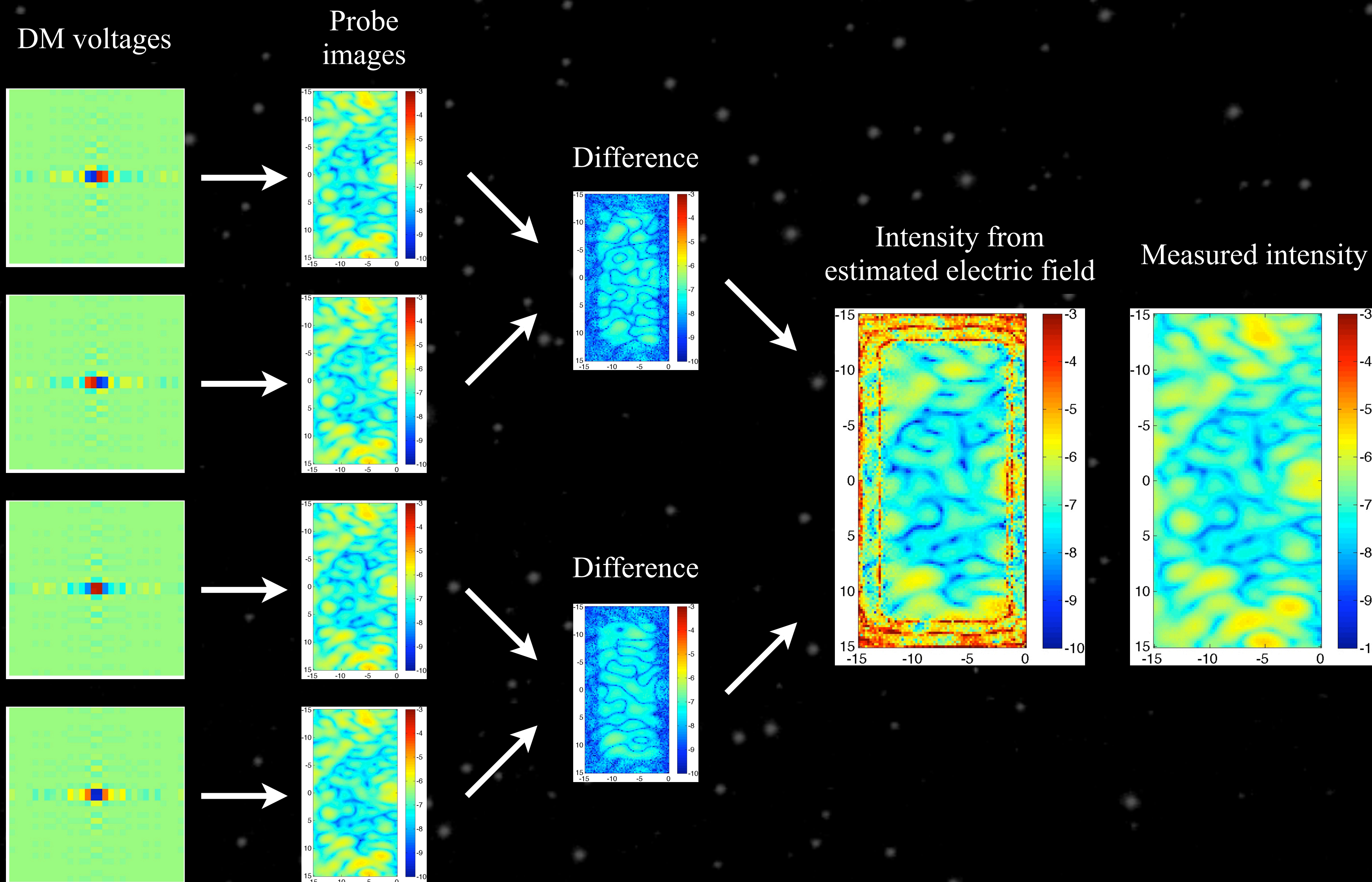
Electric Field Conjugation



Electric Field Conjugation

Take an image

Calculate average intensity in the control region

Take probe images

Reconstruct the electric field in the image plane

Simulate the non-linear system

Apply new DM settings

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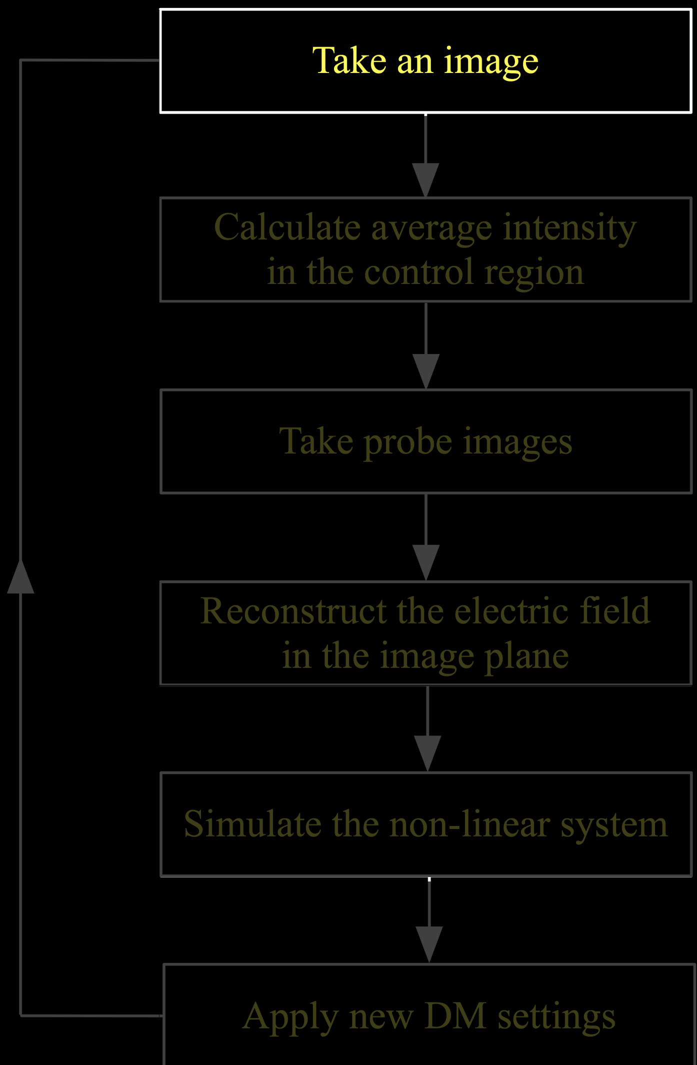
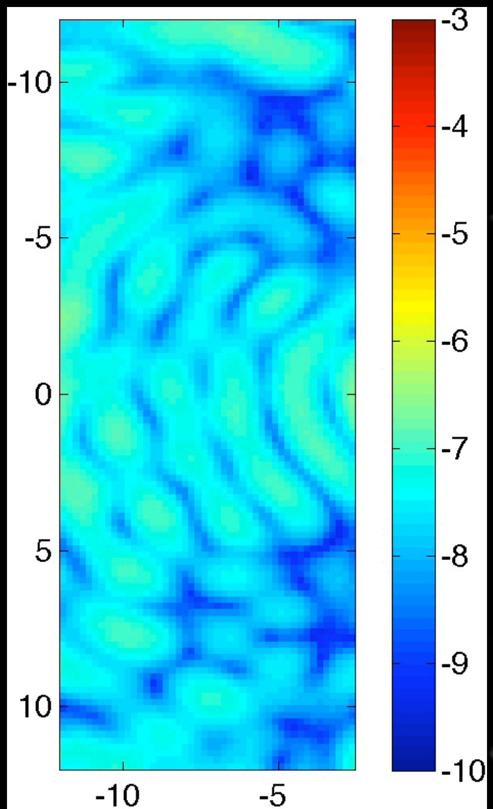
Electric Field Conjugation



Measured image

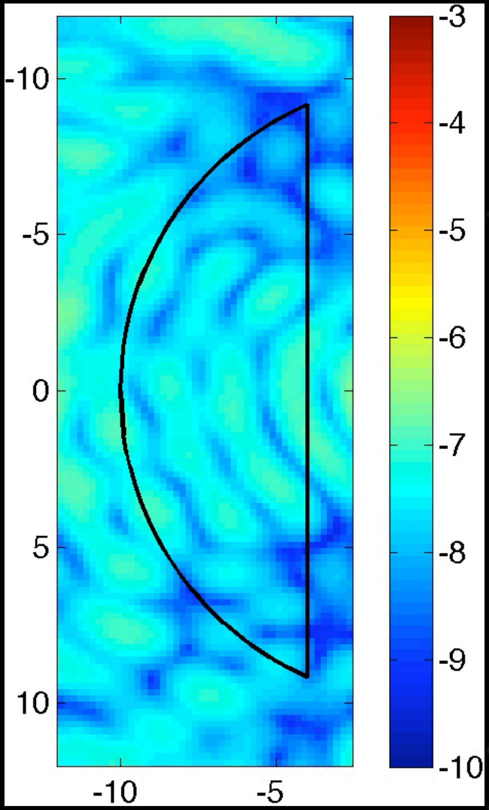


Measurements were taken at 2% around 800nm

Electric Field Conjugation

- Take an image
- Calculate average intensity in the control region
- Take probe images
- Reconstruct the electric field in the image plane
- Simulate the non-linear system
- Apply new DM settings

Measured image



Measurements were taken at 2% around 800nm

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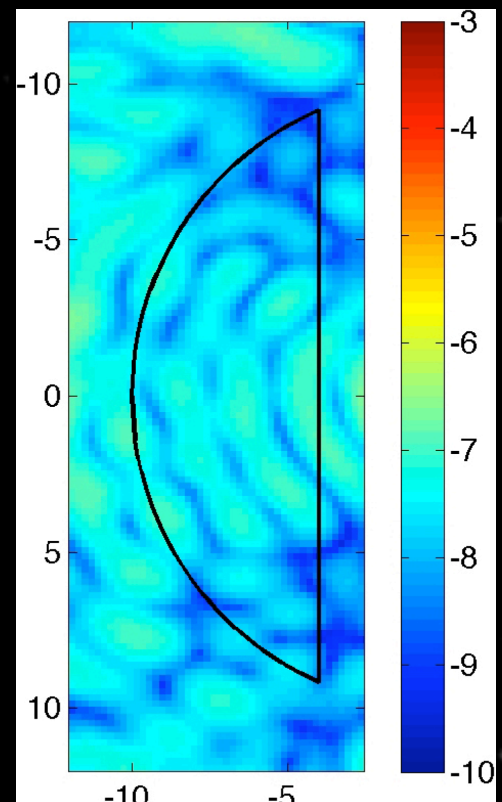
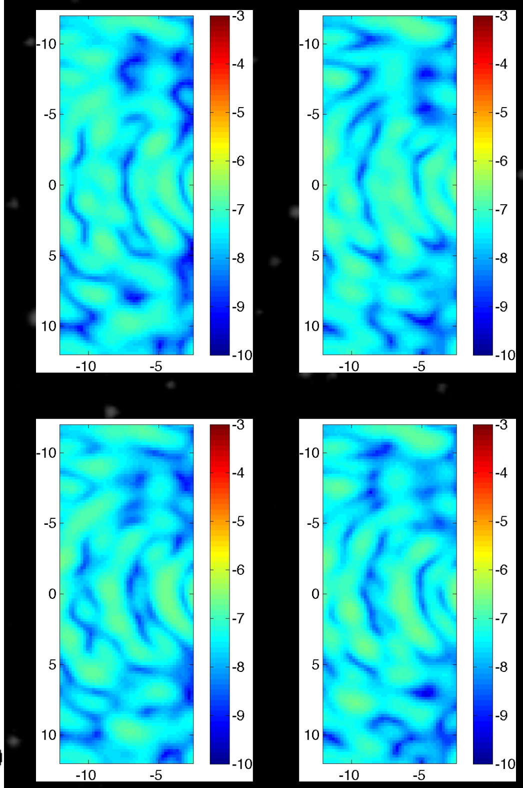
Electric Field Conjugation

- Take an image
- Calculate average intensity in the control region
- **Take probe images**
- Reconstruct the electric field in the image plane
- Simulate the non-linear system
- Apply new DM settings

Measured image



Probe images



Measurements were taken at 2% around 800nm

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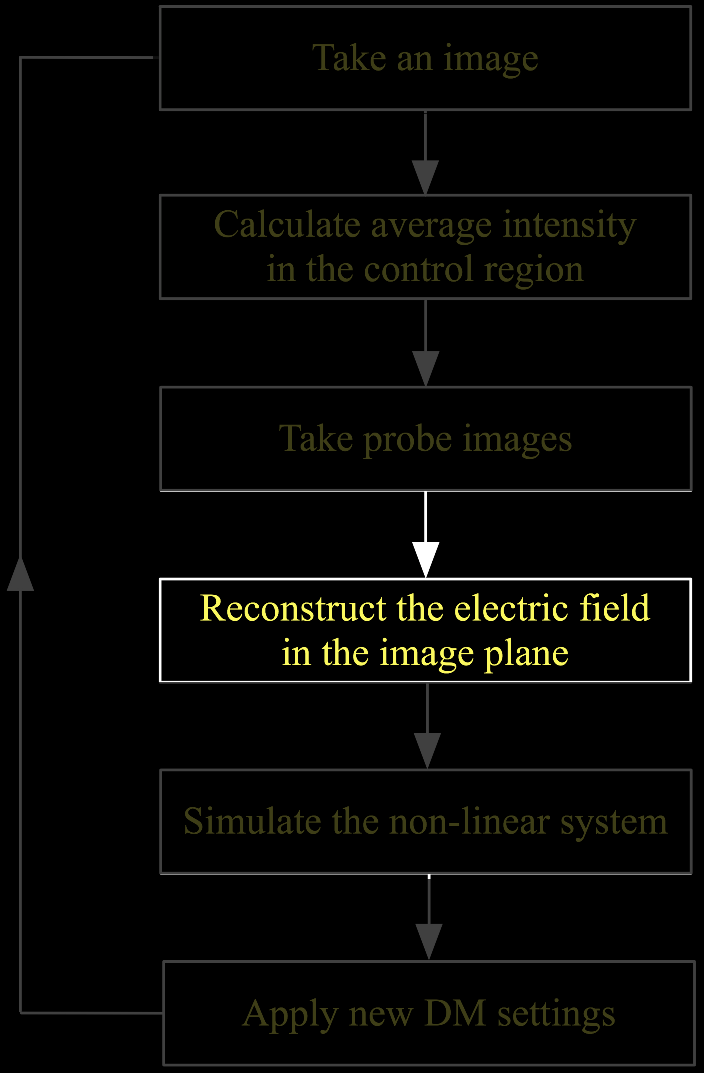
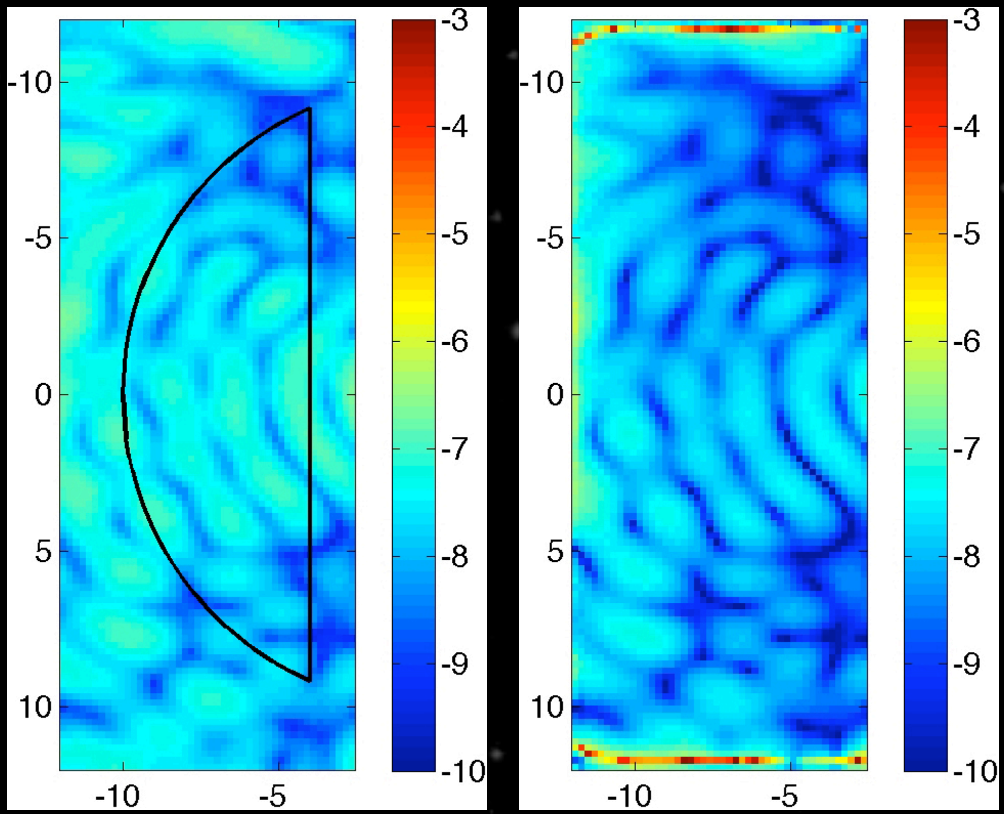
Electric Field Conjugation



Measured image

Intensity from reconstructed electric field



Measurements were taken at 2% around 800nm

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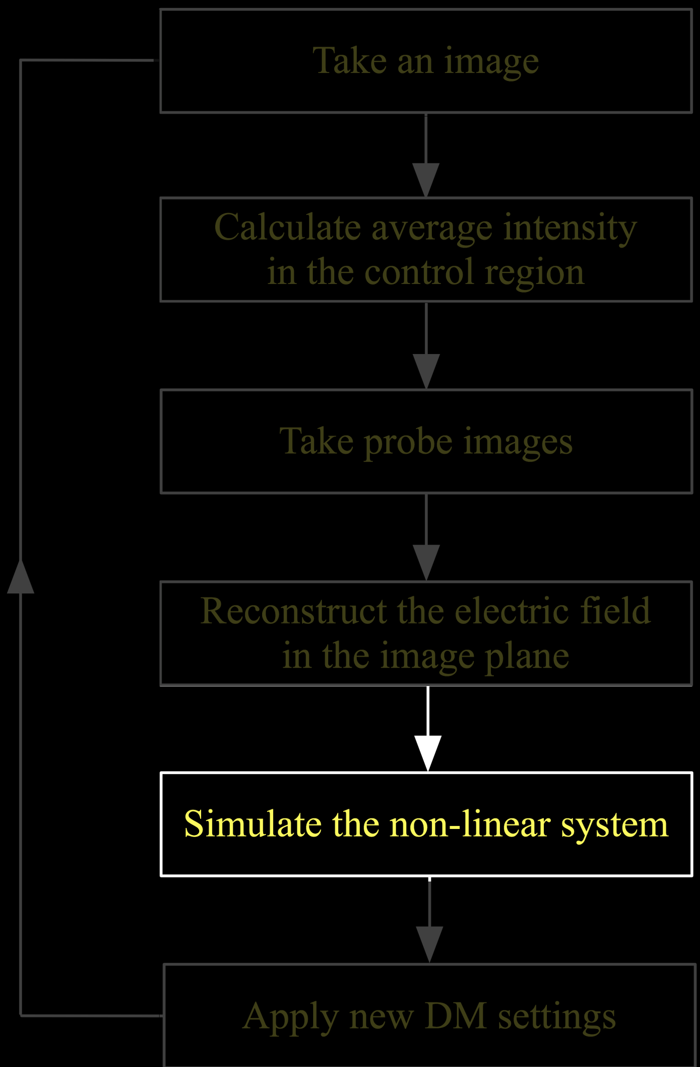
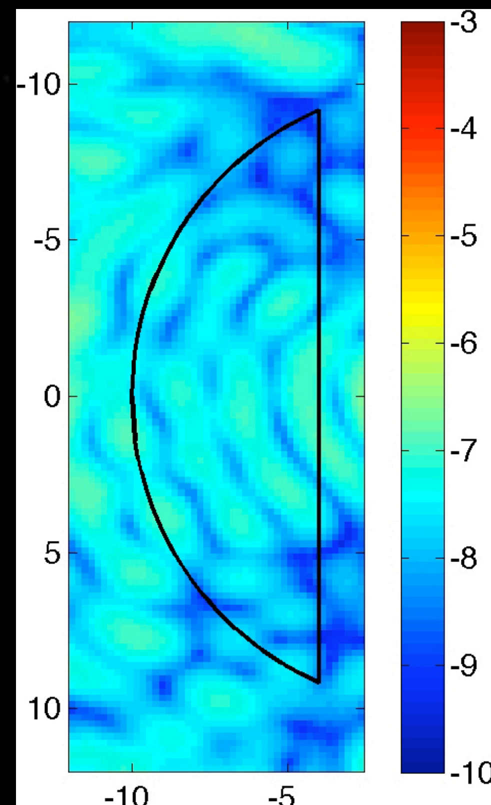
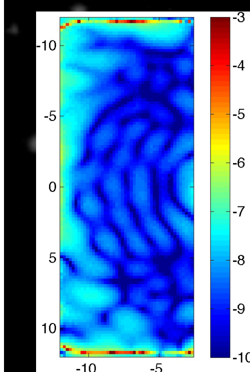
Electric Field Conjugation



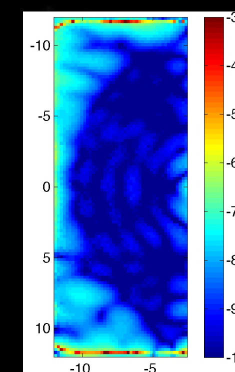
Measured image



After one iteration



After five non-linear analytic sub-steps



Measurements were taken at 2% around 800nm

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Electric Field Conjugation

Take an image

Calculate average intensity in the control region

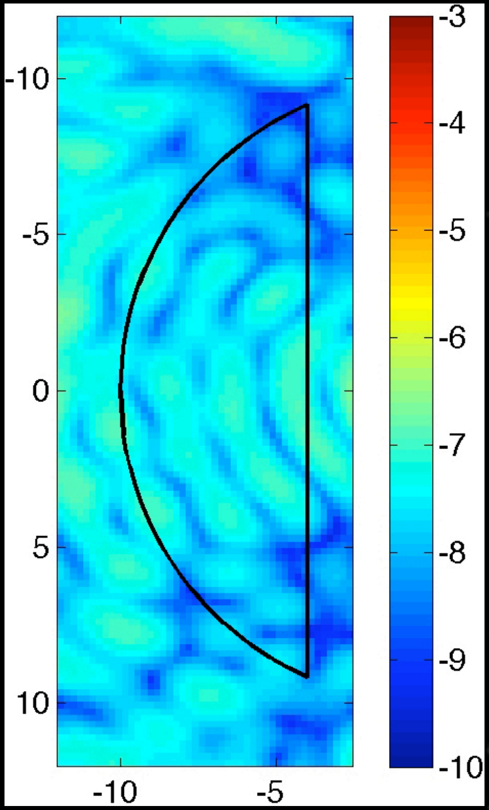
Take probe images

Reconstruct the electric field in the image plane

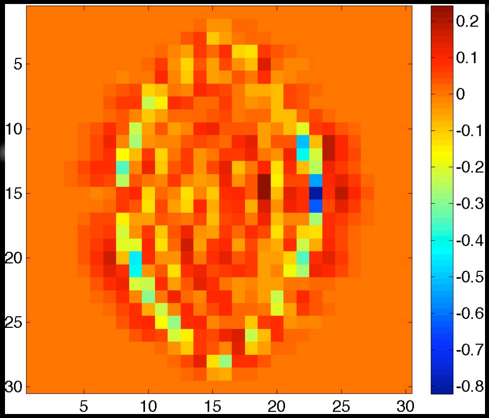
Simulate the non-linear system

Apply new DM settings

Measured image



Change in DM actuators

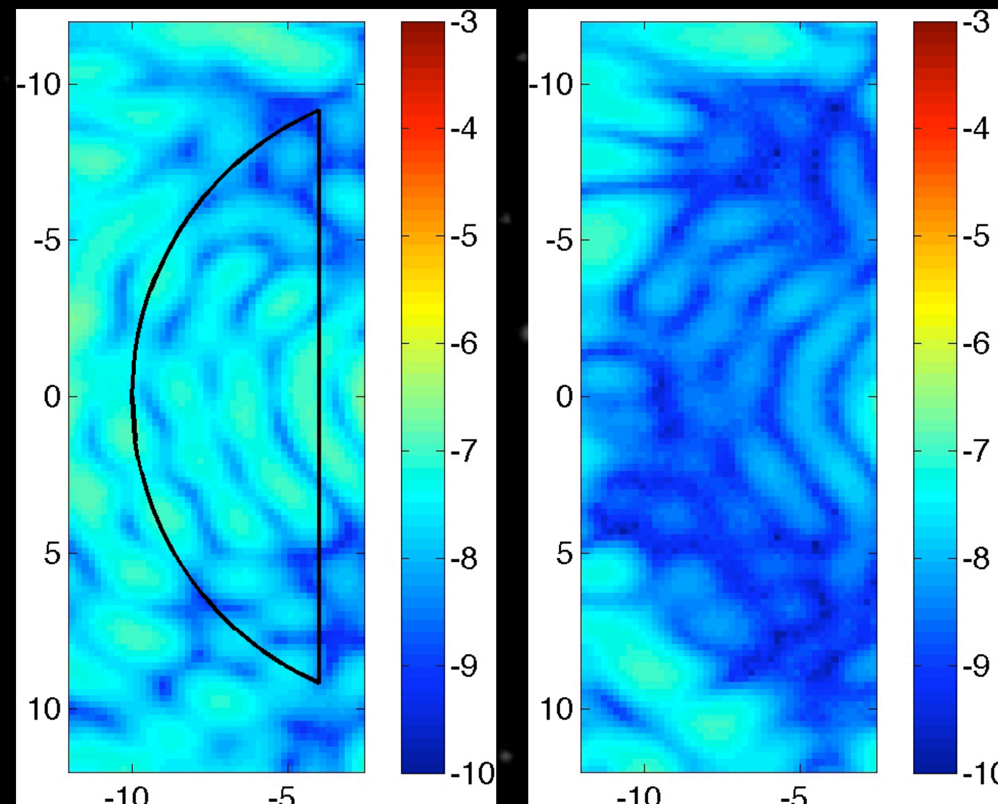


Measurements were taken at 2% around 800nm

Electric Field Conjugation

1. Take an image
2. Calculate average intensity in the control region
3. Take probe images
4. Reconstruct the electric field in the image plane
5. Simulate the non-linear system
6. Apply new DM settings

Measured image | New measured image



Measurements were taken at 2% around 800nm

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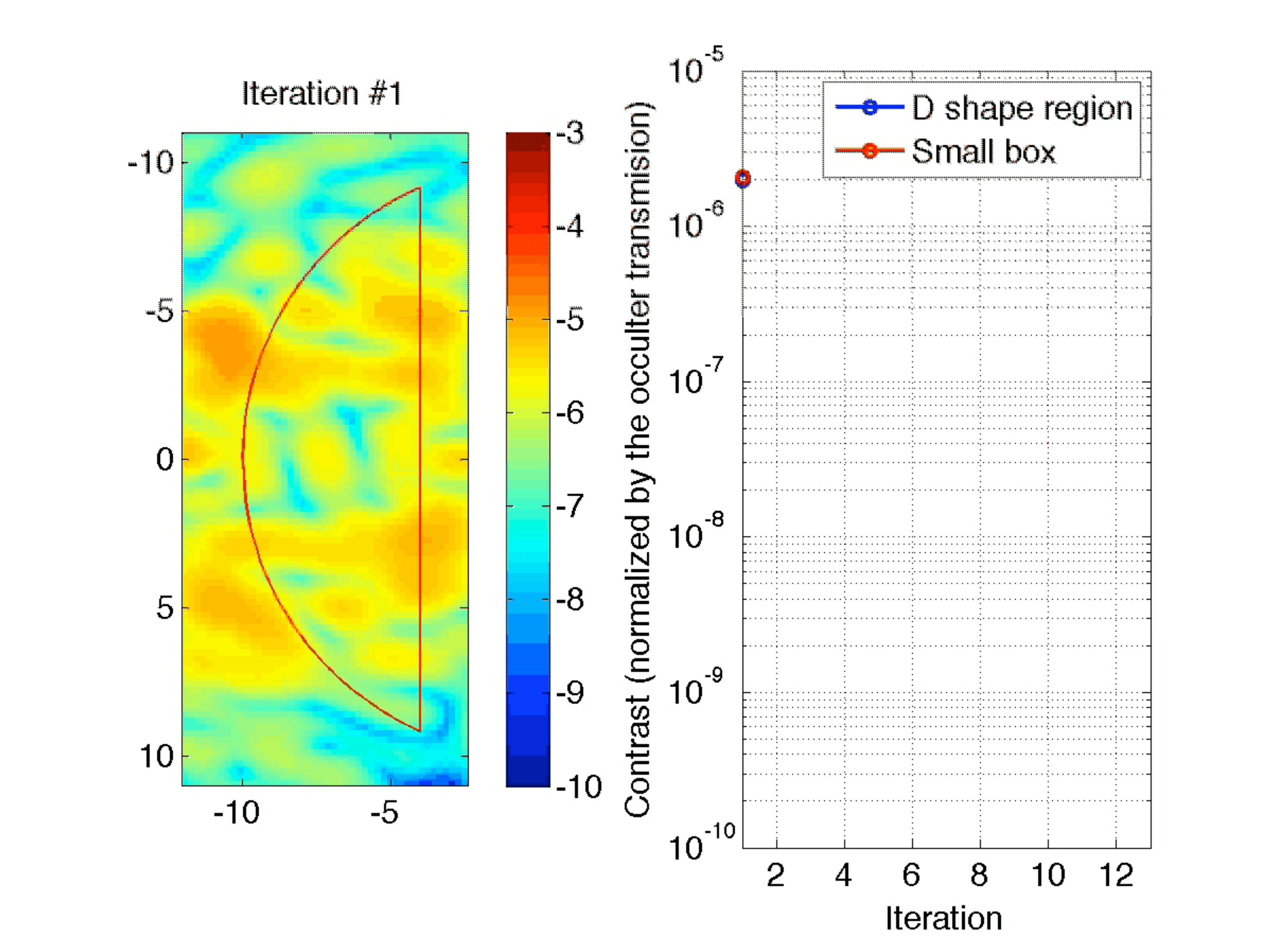
Band limited coronagraph, 2% light around 800nm

Band limited coronagraph, 2% light around 800nm



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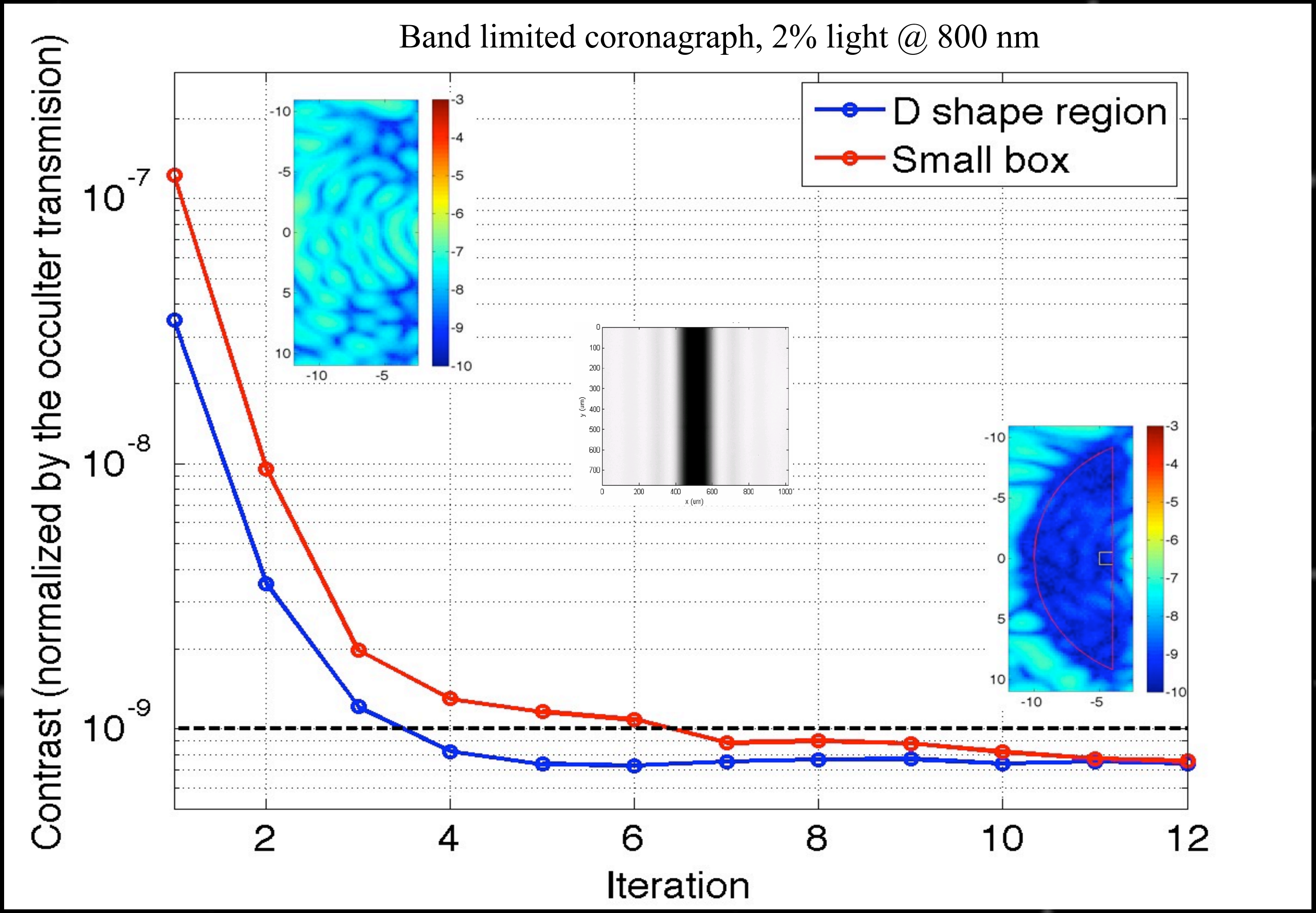
Band limited coronagraph, 2% light around 800nm



$$Contrast = 6 * 10^{-10} \;\; at \;\; 2\% \;\; light$$

$$Contrast = 4 * 10^{-10} \;\; at \;\; monochromatic \;\; light$$

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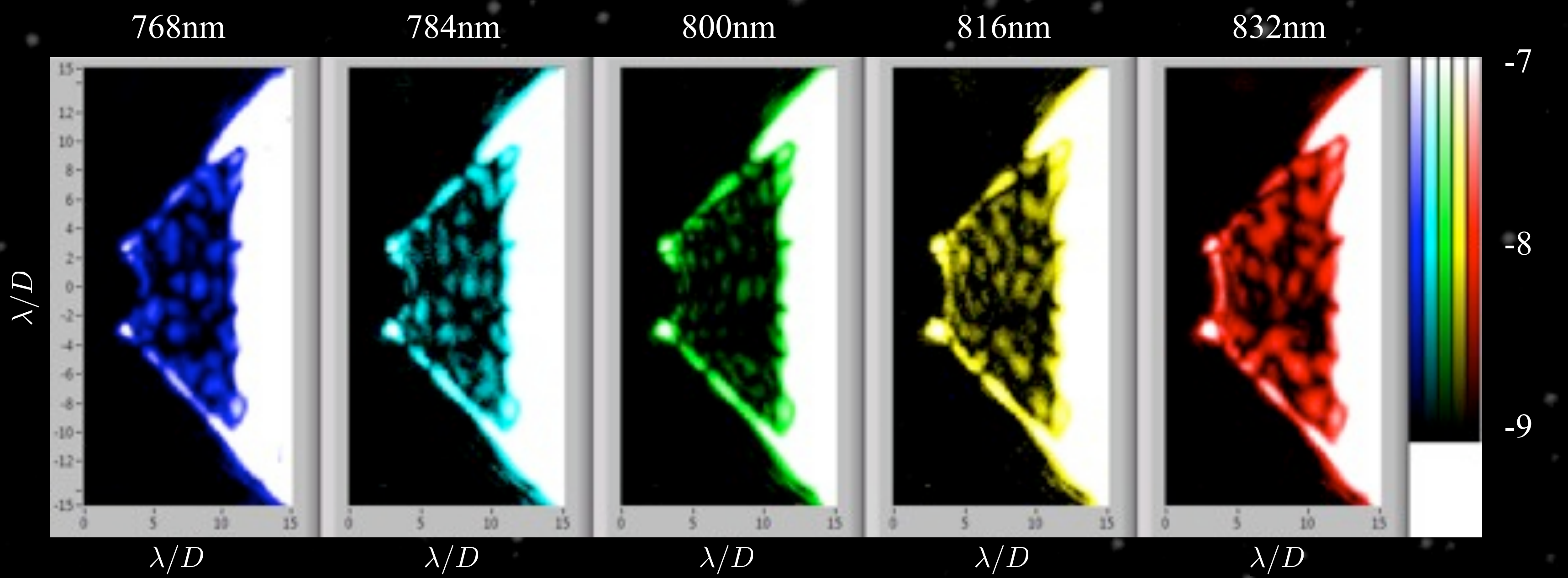
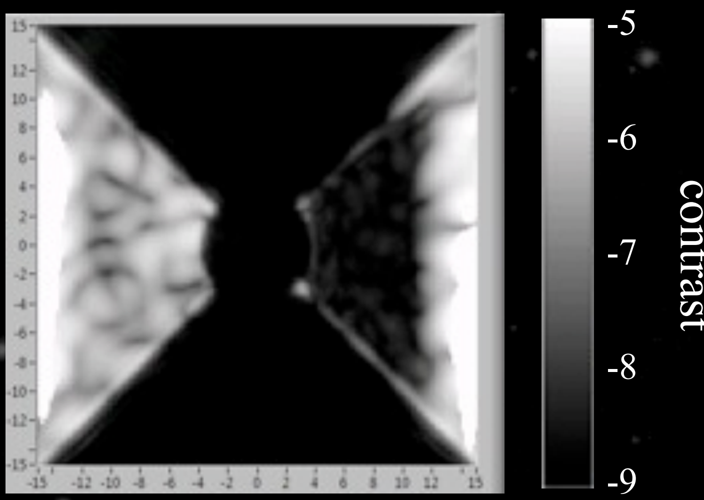
Shaped pupils are achromatic...



Broadband image (10%)
760nm - 840nm



$$Contrast = 2.37 * 10^{-9} \;\; at \;\; 10\% \;\; light$$

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Shaped pupil coronagraph, 2% light around 800nm

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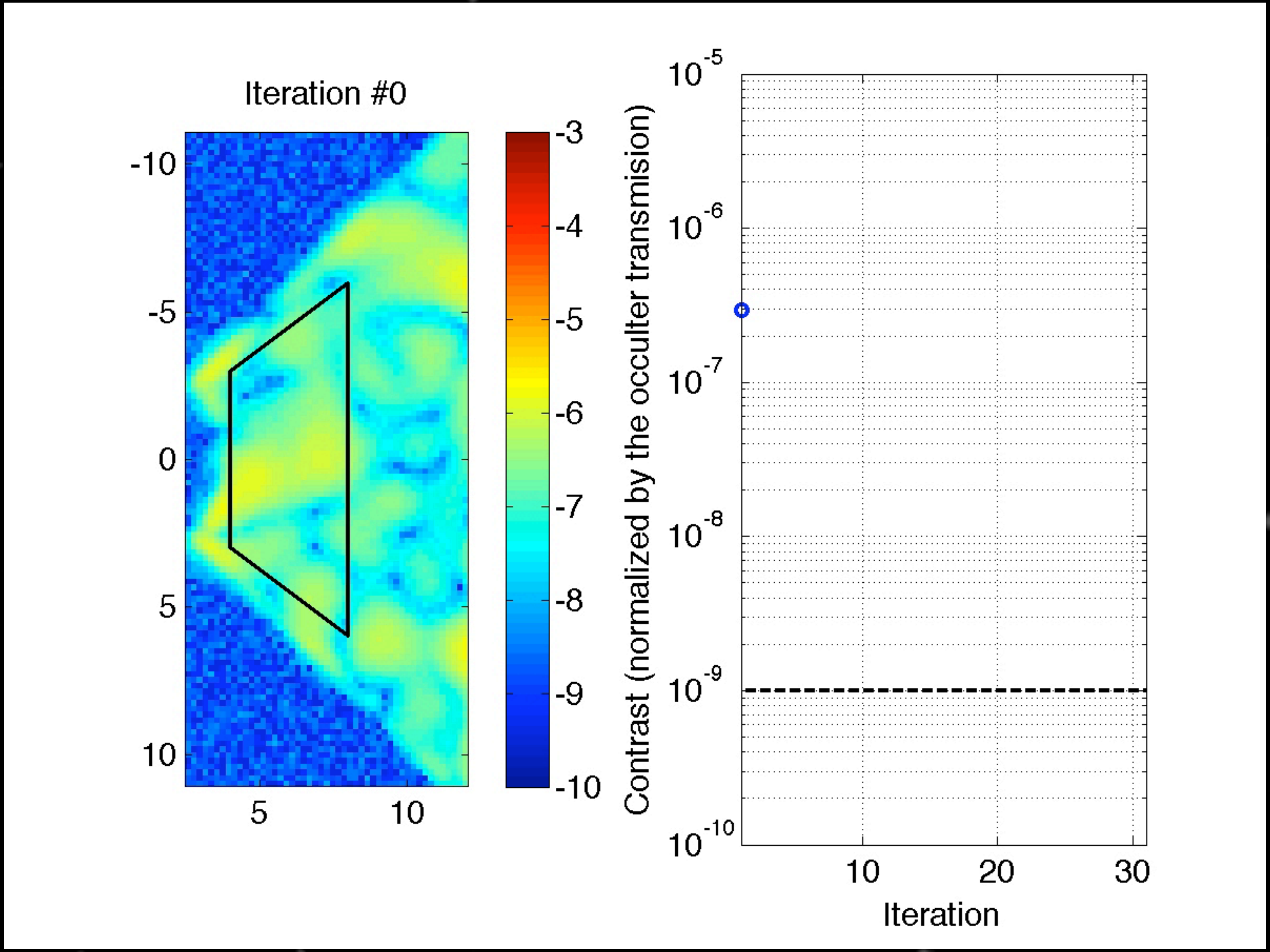
Shaped pupil coronagraph, 2% light around 800nm



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Electric Field Conjugation

(Multi wavelength correction results)

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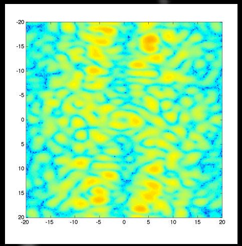
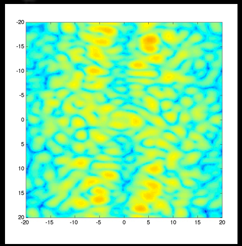
Electric Field Conjugation

(Multi wavelength correction results)

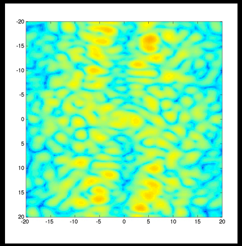
768nm



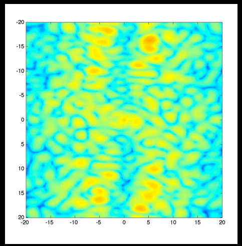
784nm



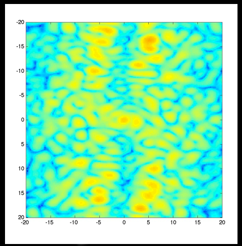
800nm

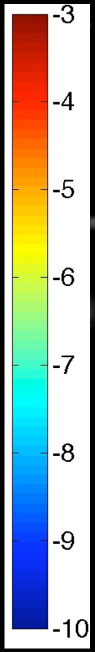


816nm

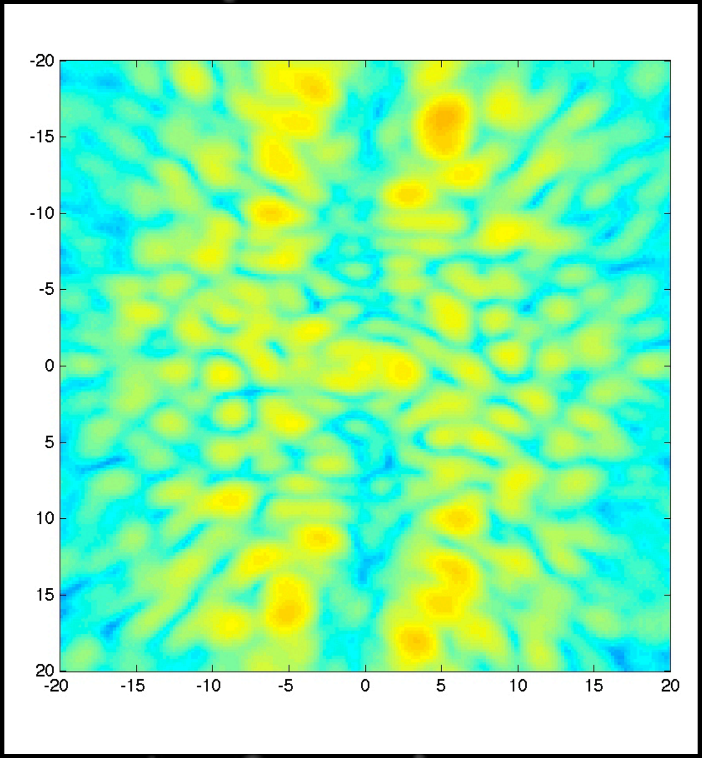


832nm





10% bandwidth around 800nm



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Electric Field Conjugation

(Multi wavelength correction results)

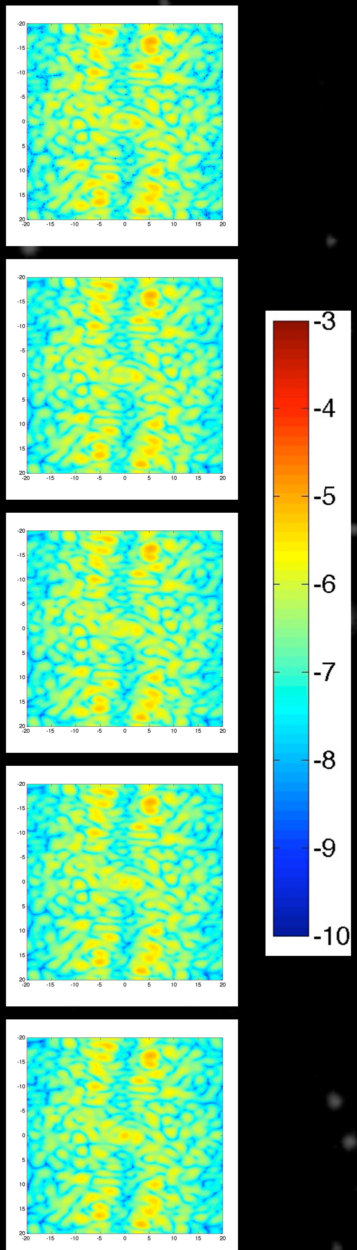
768nm

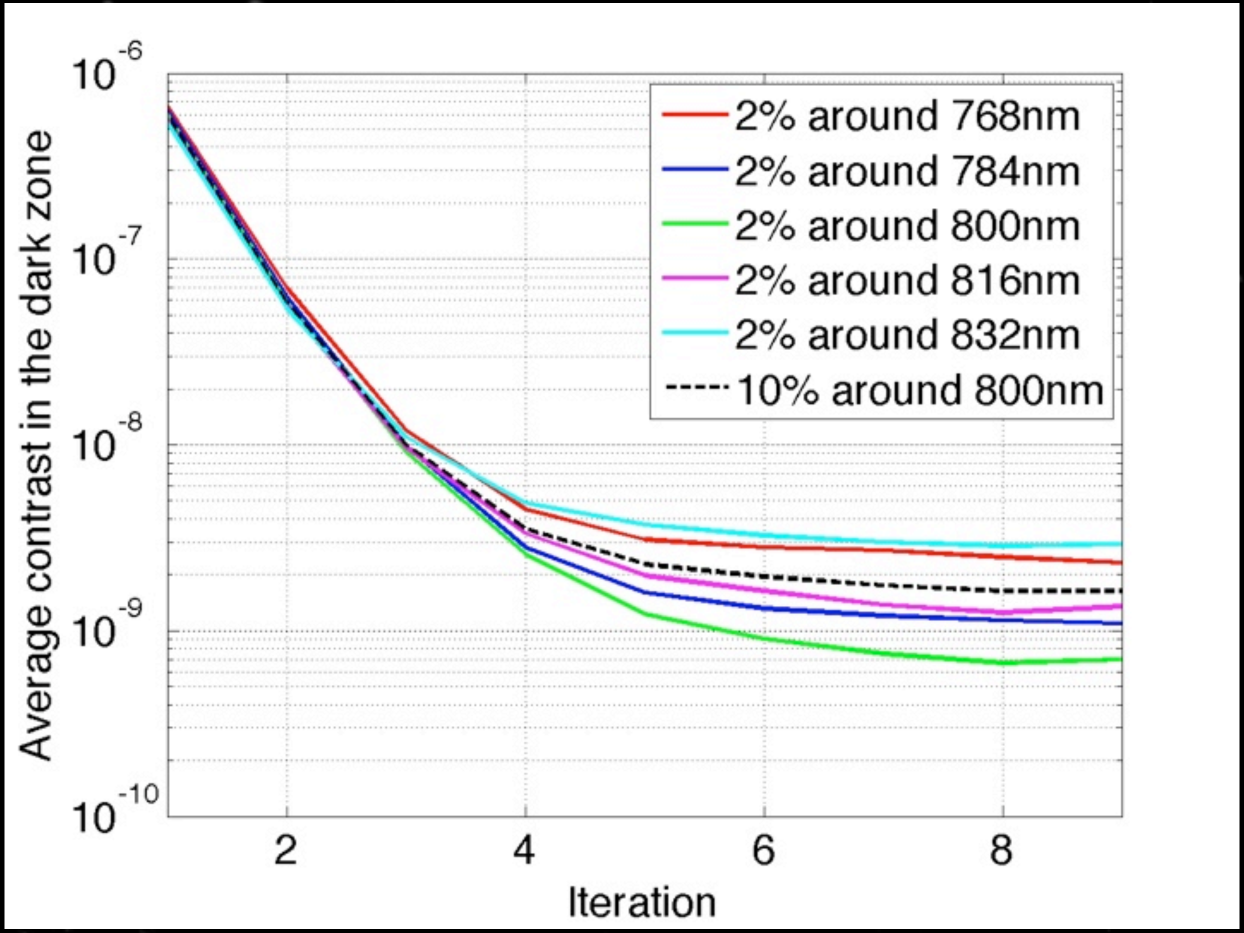
784nm

800nm

816nm

832nm





$$Contrast = 2.3 * 10^{-9} \quad at \quad 10\% \quad light$$

Electric Field Conjugation

Summary

- The reconstruction method using pairs of images has been implemented at HCIT and has been an important part of the success of reaching new record contrasts in both narrow and broad bands.
- The EFC correction algorithm has been successfully implemented at HCIT, working with both band limited coronagraphs and shaped pupils coronagraphs.
- Record contrasts have been achieved at HCIT and the Princeton testbed using these methods for reconstruction and correction.
- Future work includes implementation of the algorithm at Palomar to run along side the AO system to correct for quasi-static and static speckles.